DOCTOR OF PHILOSOPHY

Morphology of the Ankle Collateral Ligaments
Functional and Clinical Considerations

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MORPHOLOGY OF THE ANKLE COLLATERAL LIGAMENTS:

FUNCTIONAL AND CLINICAL CONSIDERATIONS

UNIVERSITY OF DUNDEE

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This thesis is submitted in fulfilment of the requirement of the degree

Doctor of Philosophy in Science in Human Anatomy

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Declaration

I, Bader Khawaji, declare that I am the author of this thesis titled “Morphology of the Ankle Collateral Ligaments: Functional and Clinical Considerations” and the work presented in it is my own. All cited references have been consulted by me, and I confirm that this work has not been accepted for the award of any other higher degree.

Bader Khawaji

Date: 22.02.2016

Statement by supervisors

I, Roger Soames, have read this thesis titled as “Morphology of the Ankle Collateral Ligaments: Functional and Clinical Considerations” and certify that the conditions of the relevant ordinance and regulations have been fulfilled.

First Supervisor: Professor Roger Soames
Date: 05.02.2016

I, Clare Lamb, have read this thesis titled as “Morphology of the Ankle Collateral Ligaments: Functional and Clinical Considerations” and certify that the conditions of the relevant ordinance and regulations have been fulfilled.

Second Supervisor: Dr Clare Lamb
Date: 23.02.2016

Publications

- **Khawaji B, Soames R. (2015) The anterior talofibular ligament: a detailed morphological study. *The Foot 25(3), 141-147***.
- Published abstracts include:
  i. **The anatomy of the superficial component of the deltoid ligament of the ankle**: presented at the winter meeting of the British Association of Clinical Anatomists 8th January 2015 at the Centre for Comparative and Clinical Anatomy, University of Bristol, Bristol.
  ii. **The deep posterior tibiotalar ligament (PTTL): a morphological study**: presented at the winter meeting of the British Association of Clinical Anatomists 8th January 2015 at the Centre for Comparative and Clinical Anatomy, University of Bristol, Bristol.
  iii. **Morphology of the calcaneofibular ligament: The influence of joint position**: presented at the winter meeting of the British Association of Clinical Anatomists 18th December 2013 at the University of Manchester.
  iv. **Anatomy of the anterior talofibular ligament (ATFL):** presented at the winter meeting of the British Association of Clinical Anatomists 20th December 2012 at the Postgraduate M Institute, Anglia Ruskin University, Essex.

➢ Copies of the paper and abstracts are included in the Appendix.

Summary

The current study aimed to investigate the anatomy and function of the ankle collateral ligaments, in order to provide a good knowledge base that could be used in clinical and biomechanical applications. Sixty eight cadaveric feet were dissected (age range: 62 – 98 years) and the morphology and ligament behaviour investigated. Data collected included the number of bands of each ligament, its dimensions, the exact proximal and distal attachment sites, the bony attachment lengths and changes in ligament length in different joint positions. The anterior talofibular ligament (ATFL) was found to have either one, two or three bands and originated 11 mm anterosuperior to the lateral malleolar tip and inserted 4.46 mm anteromedial to the anterolateral malleolar line of the talus. The ATFL limits plantarflexion, inversion and talar adduction, and internal rotation. The calcaneofibular ligament (CFL) originated 7.63 mm from the lateral malleolar tip and passed to the calcaneal lateral surface to insert 17.7 mm commonly posterosuperior to the fibular tubercle. The CFL resists dorsiflexion, eversion and fibular abduction, and external rotation. The posterior talofibular ligament (PTFL) was attached proximally to the malleolar fossa of the lateral malleolus 9.75 mm from the tip and inserted all the way into the posterolateral surface of the talus ending either lateral or lateral and posterior to the posterolateral tubercle. The PTFL restricts dorsiflexion, fibular abduction and external rotation, and talar abduction and posterior displacement.

The superficial layer of the deltoid ligament consisted of four bands which all originated from the medial malleolus: these were the tibionavicular (TNL), tibiospring (TSL), tibiocalcaneal (TCL), and superficial tibiotalar (STTL)

ligaments. The TNL widely inserted into the navicular and talus and may blend with the spring ligament; the TSL commonly attached to the spring ligament and sustentaculum tali; the TCL inserted distally into the sustentaculum tali and talar posteromedial tubercle; the STTL, which was absent in 7.8% of specimens, had a common distal attachment to the talar medial surface and talar posteromedial tubercle. The TNL limits plantarflexion, inversion and talar adduction and internal rotation; the TSL supports the head of the talus and may have isometric characteristics; the TCL and STTL restrict dorsiflexion, eversion, talar abduction and external rotation, and tibial internal rotation.

The deep component of the deltoid ligament consisted of the constant posterior tibiotalar ligament (one to four bands) (PTTL) and the anterior tibiotalar ligament (one or two bands) (ATTL), which was absent in 3.3% of specimens. The PTTL originated between the anterior and posterior colliculi filling the intercollicular groove of the medial malleolus, while the ATTL originated from the medial malleolus commonly from the tip, the anterior and medial surfaces of the anterior colliculus. Both deep layer components inserted distally into the talar medial surface commonly anterosuperior to the talar posteromedial tubercle. The PTTL limits dorsiflexion, eversion, talar abduction and external rotation, and tibial internal rotation, while the ATTL may restrict plantarflexion, inversion, talar internal rotation and adduction, and tibial external rotation. The findings of the present study may aid in the diagnosis and surgical treatment of ankle collateral ligaments injuries. Furthermore, they may help in understanding of the mechanism of injury and provide a good knowledge base for the development of appropriate injury prevention methodology or devices.

Acknowledgements

In the beginning, I would like to thank Allah the Almighty God for the great grace and helping me in the completion of this work. I would like to express my appreciation and thanks to my supervisors: Professor Roger Soames and Dr Clare Lamb; you have been wonderful mentors for me; I thank you for all the encouragement and guidance you have provided me and for your patience that has helped me to grow to become a confident research scientist. I would also like to thank my thesis committee members Professor Sue Black and Professor Niamh Nic Daeid for their time, encouragement and the guidance they gave to me. A special thanks to everyone in the Centre for Anatomy and Human Identification at the University of Dundee, for all the support and aid that they provided which helped me during the writing of my PhD thesis. This research used samples from human cadavers who had donated their bodies to the department for teaching and scientific research; with your unselfishness this research would not have been possible. I also thank Dr Weijie Wang for his continuous help and support in the statistical analysis of the data that was collected in this study.

Special thanks to my father and mother for believing in me, for their support as well as for their prayers. I would like to thank my wife who sacrificed her time and effort to provide me with the appropriate atmosphere that helped in the completion of this thesis; my wife and my son gave me love, care and laughs which helped me become stronger to cope with the different obstacles. Finally, I would like to thank my siblings, friends and loved ones for believing in me, their support and suggestions have helped me in the completion of this work.

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List of Abbreviations

AATTL: anterior band of the ATTL

AC: anterior colliculus of the medial malleolus

ALML: anterolateral malleolar line of the talus

APTTL: anterior band of the PTTL

ATFL: anterior talofibular ligament

ATTL: deep anterior tibiotalar ligament

CFL: calcaneofibular ligament

DBA: distal bony attachment length

FROM: functional range of motion

FT: fibular tubercle of the calcaneus

IATFL: inferior band of the ATFL

L0: ligament length when it starts functioning

Ln: Ligament length at the neutral position

LTCL: lateral talocalcaneal ligament

MATFL: middle band of the ATFL

MPTTL: middle band of the PTTL

MRI: magnetic resonance imaging

NBA: no bony attachment length

PATTL: posterior band of the ATTL

PBA: proximal bony attachment length

PC: posterior colliculus of the medial malleolus

PLT: posterolateral tubercle of the talus

PMT: posteromedial tubercle of talus

PPTTL: posterior band of the PTTL

PTFL: posterior talofibular ligament

PTTL (dPTTL): deep posterior tibiotalar ligament

ROM: range of motion

SATFL: superior band of the ATFL

ST: sustentaculum tali of the calcaneus

STTL (sPTTL): superficial tibiotalar ligament

TCL: tibiocalcaneal ligament

TNL: tibionavicular ligament

TSL: tibiospring ligament

US: ultrasound

1 Introduction

Ankle injuries and sprain are reported to be one of the most common injuries, especially in sports (Bortzman and Manske, 2011; Fong et al., 2007) and dancing (Russell, 2010) activities. Ankle sprains affecting the ligaments commonly affect the lateral collateral ligaments (LCL), while the medial collateral ligaments (deltoid) have been reported to be injured in association with LCL injuries, fractures or cases of flatfoot acquired valgus deformity. Ankle instability is one of the main proplems that patients with ankle injuries may develop as a result of injured collateral ligaments not providing the appropriate stability (Peters et al., 1991). A good knowledge base of the functional anatomy of the ankle collateral ligaments is therefore essential in understanding the mechanism of injuries, diagnosing, treating and preventing injuries to the collateral ligaments of the ankle.

There has been either disagreement or a lack of anatomical descriptions in the literature, with variable morphological descriptions being reported in previous investigations including disagreement about the number of ligament bands, their dimensions, and the exact bony attachment sites. In addition, there is a lack of detail of the ligaments' bony attachment lengths as well as their behaviour and function in different ankle and subtalar joint positions. Therefore, the current study investigated the functional anatomy of the lateral and medial collateral ligaments of the ankle in an attempt to address the gaps in the literature, as well as analysing the functional roles of these ligaments and discussing the different clinical interpretations.

1.1 Aims and Objectives of the Study

- Study the morphology and variations of the lateral and medial collateral ligaments of the ankle.
- Determine the exact proximal and distal bony attachment sites of the lateral and medial collateral ligaments.
- Determine the free length or no bony attachment (NBA), proximal (PBA) and distal (DBA) bony attachments of each part of each collateral ligament.
- Examine the changes in ligaments’ absolute length in different joint positions.
- Investigate the ligaments’ functions by considering the morphology and ligament behaviour in different joint positions.
- Provide a sound anatomical knowledge that can be used and interpreted by clinicians, radiologists, physiotherapists, orthotic specialists, rehabilitation providers and sport shoe makers.

1.2 Thesis Outline

This thesis consists of eight chapters. Chapter 1 is the introduction as well as presenting the aims and objectives behind the research conducted. Chapter two reviews the relevant literature starting with the basic anatomy of the leg and tarsal bones, as well as ankle and subtalar joints. In this chapter, section two concerns the movements and stability of the ankle and subtalar joints discussing these in detail; sections three, four and five concern the previously discussed anatomical descriptions of the components of the lateral collateral ligaments, i.e. the anterior (ATFL) and posterior (PTFL) talofibular ligaments and calcaneofibular ligament (CFL), by reviewing variations in the reported number of bands, their proximal and distal bony attachment sites, as well as the ligaments dimensions. Section six reports on the anatomy of the medial collateral ligament (deltoid) and includes the various components and shape of the deltoid ligament: it also reviews the anatomical descriptions of the different bands of both superficial and deep layers. Section seven discusses the role of the collateral ligaments, including (i) strains of the ligaments, (ii) their isometric characters, (iii) which reviews studies on ligament transection, and (iv) the reported function and innervation of the ligaments. The final section in chapter two discusses the clinical aspects of injuries to the ankle collateral ligaments, including (i) epidemiology, (ii) mechanisms of injury, (iii) ankle instability, (iv) diagnosis, (v) conservative treatment, (vi) surgical treatment of the injured lateral collateral ligaments, (vii) surgical treatment of the injuredmedial collateral ligaments and (viii) preventative methods.

Chapter three covers the materials and methodology used to conduct the study. It considers the sample and instruments used in the research; the preparation and dissection of the specimens; the methodology used in obtaining the different qualitative observations and quantitative measurements; in addition, it explains how the methodology was tested for reliability and the statistical analysis of the data collected. Chapter four presents the findings of the various investigations starting with the presentation of the reliability findings and then reports all the findings for all ligaments.

Chapter five discusses these findings and compares them to previous reports. Additionally, the morphology of each ligament is discussed in sections one to six. Section seven of this chapter discusses the different functional aspects of the ligaments in relation to the study findings as well as previous reports; the behaviour of individual ligaments or bands of the collateral ligaments was analysed and the function of each is discussed. Section eight discusses the relevant clinical aspects where comments and suggestions are given. Chapter six presents the conclusions of the study highlighting the main findings and interpretations.

2 Literature Review

2.1 Basic Anatomy

2.1.1 Leg and Tarsal Bones

The tibia is the medial weightbearing bone of the leg. It articulates with the femur proximally, forming the knee joint, and talus distally, and forms part of the ankle joint. The tibia ends distally forming the medial malleolus (Figure 2.1) (Gunn, 2007).

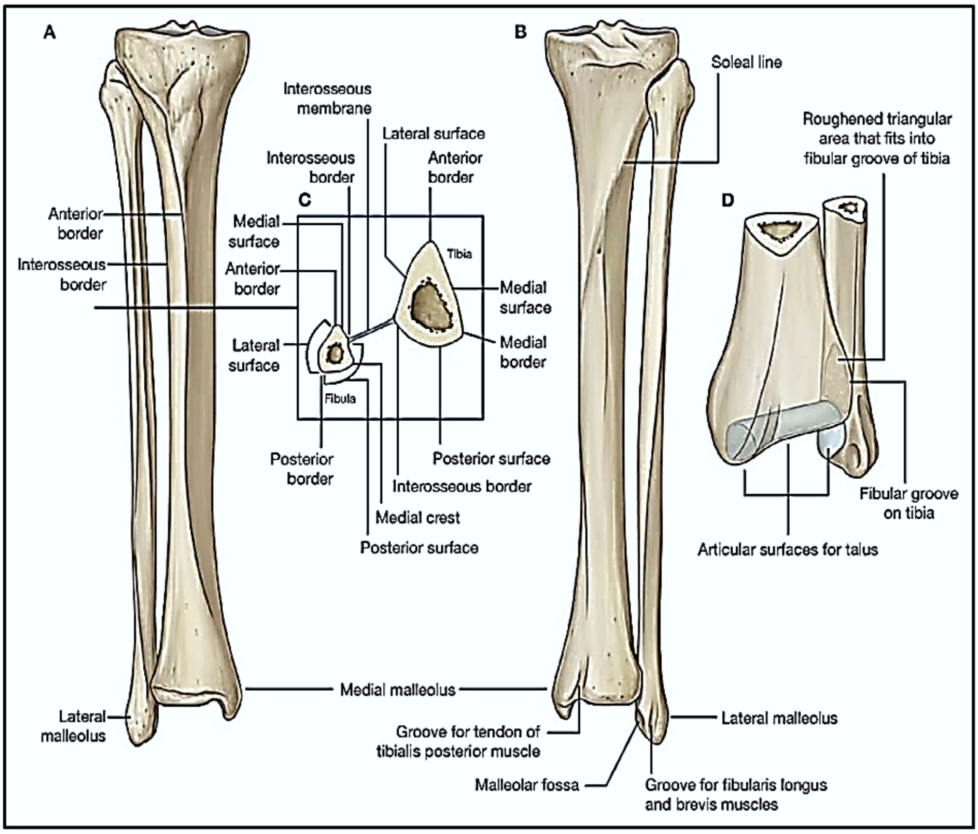

Figure 2.1 Morphology of the tibia and fibula: A, anterior view; B, posterior view; C,,cross section view; D, Posteromedial view of the lower end (Drake et al., 2010b).

The fibula is the lateral bone of the leg which articulates with the tibia forming the superior and inferior tibiofibular joints (Figure 2.1). It extends distally as the lateral malleolus which articulates with the talus forming part of the ankle joint. The posterior part of the medial side of the inferior end of the fibula has a depression, the malleolar fossa (Gunn, 2007). The tip of the lateral malleolus descends more distally compared to the medial malleolus (Standring, 2008a).

Between the tibia and metatarsal bones are the tarsal bones (Figure 2.2), with the talus and calcaneus constituting the proximal row and the navicular, cuboid and the three cuneiform bones forming the distal row. The talus articulates with the tibia, fibula, calcaneus and navicular, while the calcaneus articulates with the talus and cuboid. In addition, the cuboid articulates with the calcaneus, navicular, lateral cuneiform, 4^{th} and 5^{th} metatarsals, while the navicular has articulations with the talus, cuboid and the three cuneiforms. The medial cuneiform articulates with the navicular, intermediate cuneiform, 1^{st} and 2^{nd} metatarsals, while the intermediate cuneiform articulates with the other cuneiforms, navicular and 2^{nd} metatarsal (Gunn, 2007).

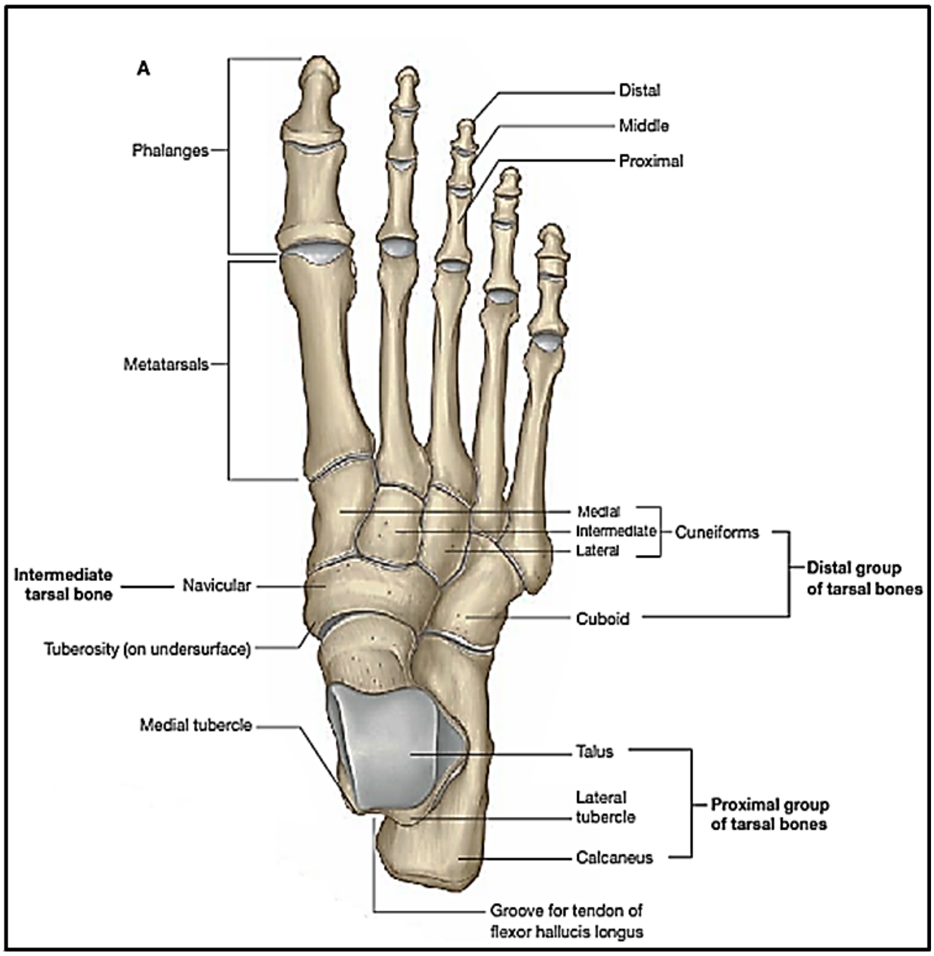

Figure 2.2 Bones of the foot (Drake et al., 2010b).

The talus (Figure 2.3) has a head, neck and body: the distal head articulates with the navicular, the neck is posterior to the head and the body is cuboidal (Gunn, 2007) with superior, inferior, medial, lateral and posterior surfaces. The superior surface is pulley-shaped and articulates with the tibia and the transverse part of the posterior and inferior tibiofibular ligaments (Sarrafian, 1993a). On its inferior surface the talus has anterior, middle and posterior articular facets which articulate with the calcaneus creating the talocalcaneal (subtalar) joint: between the middle and posterior articular facets is the sulcus tali (Gunn, 2007). The lateral surface is trigonal to which the anterior talofibular ligament (ATFL) inserts on to its anterior border via two tubercles, or a depression or notch (Sarrafian, 1993a). The lateral (posterolateral) and medial (posteromedial) tubercles of the talus on the inferomedial aspect of the posterior surface are separated by a groove for the tendon of flexor hallucis longus (Palastanga et al., 2006). The talus has no muscle attachments, but instead acts to transfer bodyweight from the tibia to the foot (Hansen, 2014).

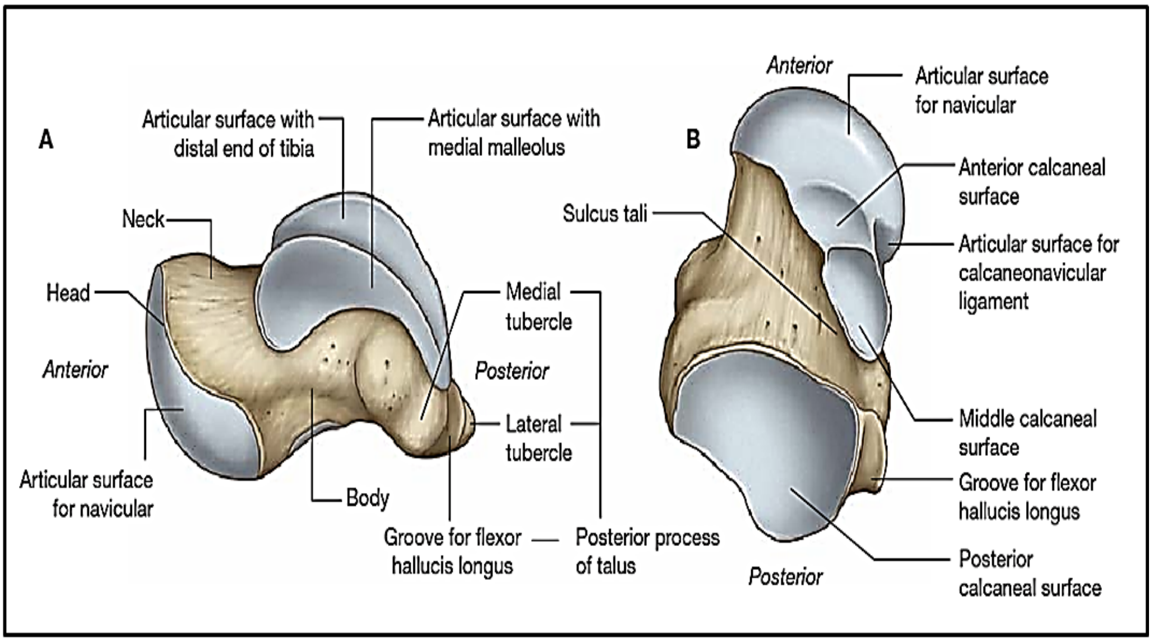

Figure 2.3 Morphology of the talus: A, medial view; B, inferior view (Drake et al., 2010b).

The calcaneus (Figure 2.4) is the largest of the tarsal bones (Thompson, 2010; Drake et al., 2012) and forms the subtalar joint with talus superiorly and the calcaneocuboid joint anteriorly with the cuboid (Sinnatamby, 2011). Its lateral surface is characterised by the fibular tubercle (FT), either side of which run the two fibularis tendons (Thompson, 2010): the calcaneofibular ligament (CFL) inserts posterior to the tubercle (Sinnatamby, 2011). The medial surface has the sustentaculum tali (ST) just superior to the tendon of flexor hallucis longus and deep to the tendon of flexor digitorum longus. The spring (plantar calcaneonavicular) ligament and the superficial deltoid ligament attach to the sustentaculum tali anteriorly and posteriorly respectively (Sinnatamby, 2011). The calcaneal tendon attaches to the posterior surface of the calcaneus (Moore et al., 2010).

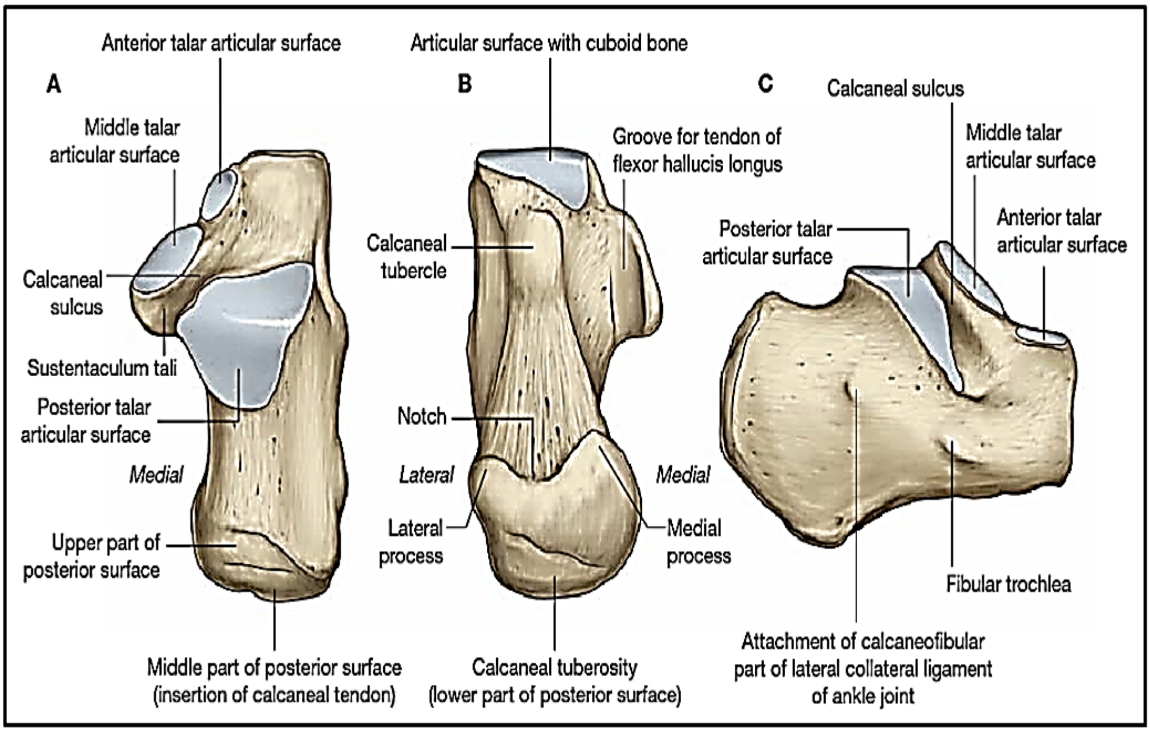

Figure 2.4 Morphology of the calcaneus: A, superior view; B, inferior view; C, lateral view (modified from Drake et al., 2010b).

The navicular bone is located between the three cuneiforms and the talar head (Moore et al., 2010).The navicular tuberosity is situated on its medial side to which the major part of tibialis posterior is attached (Snell, 2008). Facets on the three cuneiforms articulate with the navicular forming the cuneonavicular joint.

The inferior tibiofibular joint (Figures 2.5 and 2.6) is a complex structure (Bartoníček, 2003), being a fibrous joint resulting from the articulation between the distal end of the fibula and the fibular notch of the tibia. It helps to maintain the relationship between the tibia and fibula by keeping the malleolar mortise of the ankle stable. The inferior tibiofibular joint is supported by transverse, anterior and posterior tibiofibular ligaments, as well as the interosseous ligament which is continuous with the interosseous membrane proximally (Palastanga et al., 2006).

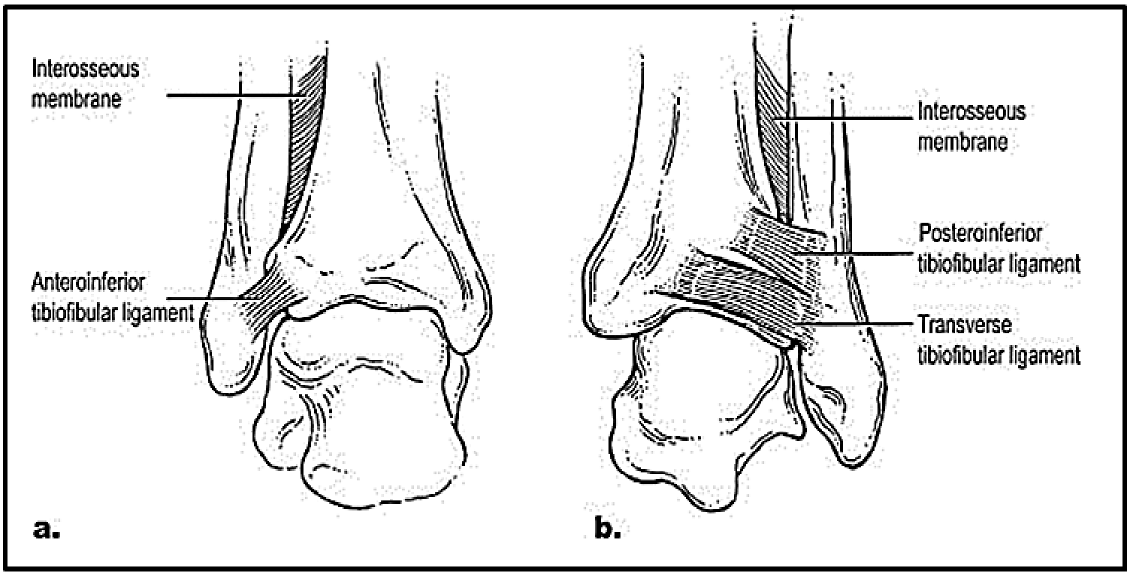

Figure 2.5 Anterior (a) and posterior (b) tibiofibular syndesmoses showing the anterior (anteroinferior), posterior (posteroinferior) and transverse tibiofibular ligaments (McKeon et al., 2012).

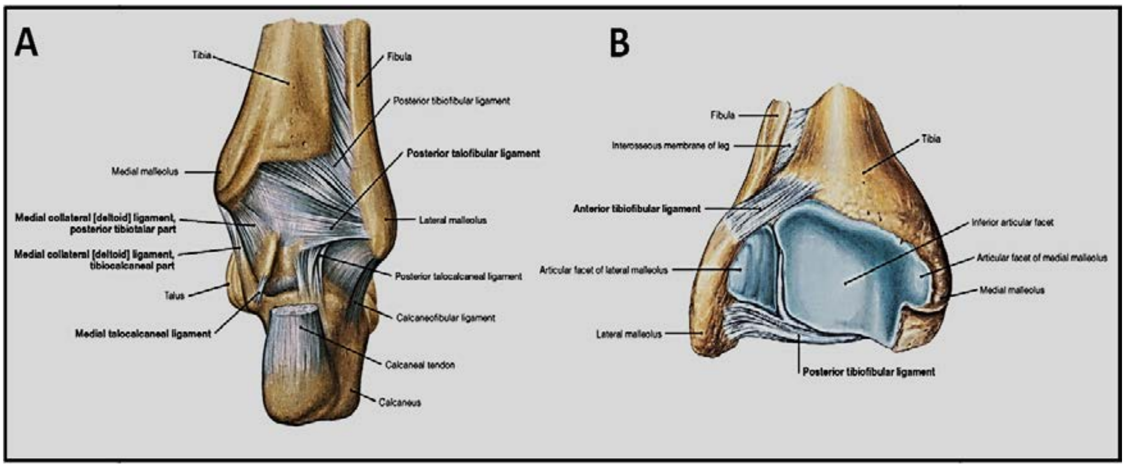

Figure 2.6 A, posterior view of the ankle joint; B, inferior view of the malleolar mortise of the ankle joint showing the tibiofibular ligaments (Paulsen and Waschke, 2013).

In dorsiflexion, the distance between the two malleoli widens as the talus moves posteriorly into the narrower part of the tibiofibular joint thus securing the talus between the two malleoli. This increases tension in the anterior, posterior, transverse and interosseous tibiofibular ligaments. On the other hand, when the ankle is plantarflexed, the lower ends of the tibia and the fibula become closer to each other as a result of tension in the anterior, posterior and interosseous ligaments gripping the talus as it moves anteriorly to the wider area of the joint: side to side movement of the talus may occur in maximal plantarflexion (Palastanga et al., 2006).

2.1.2 Ankle and Subtalar Joints

The ankle joint (Figure 2.7) is a hinge joint between the articulation of the two malleoli and the articular surface of the talus (Moses et al., 2013): dorsiflexion (20°) and plantarflexion (50°) occur at the joint (Thompson, 2010). The joint is supported by the medial and lateral collateral ligaments (Figure 2.8). The lateral collateral ligament includes the anterior talofibular (ATFL), calcaneofibular (CFL) and posterior talofibular (PTFL) ligaments, while the medial collateral (deltoid) ligament is a strong triangular structure (Moore and Roy, 2012).

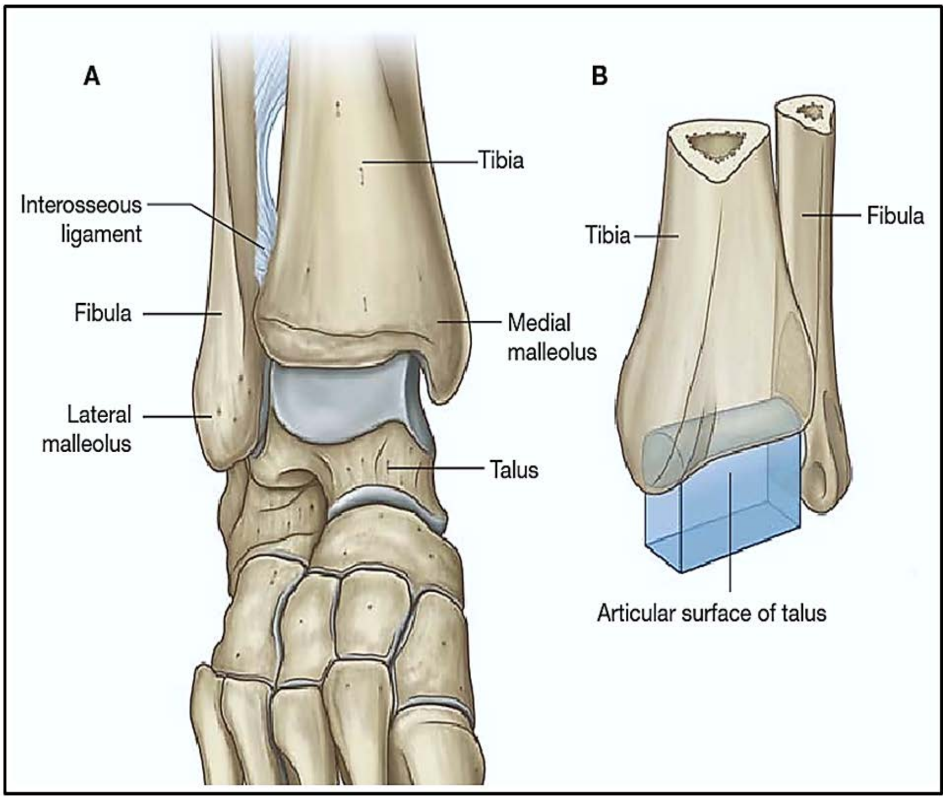

Figure 2.7 Ankle joint: A, anterior view; B, schematic view for the joint (modified from Drake et al., 2010b).

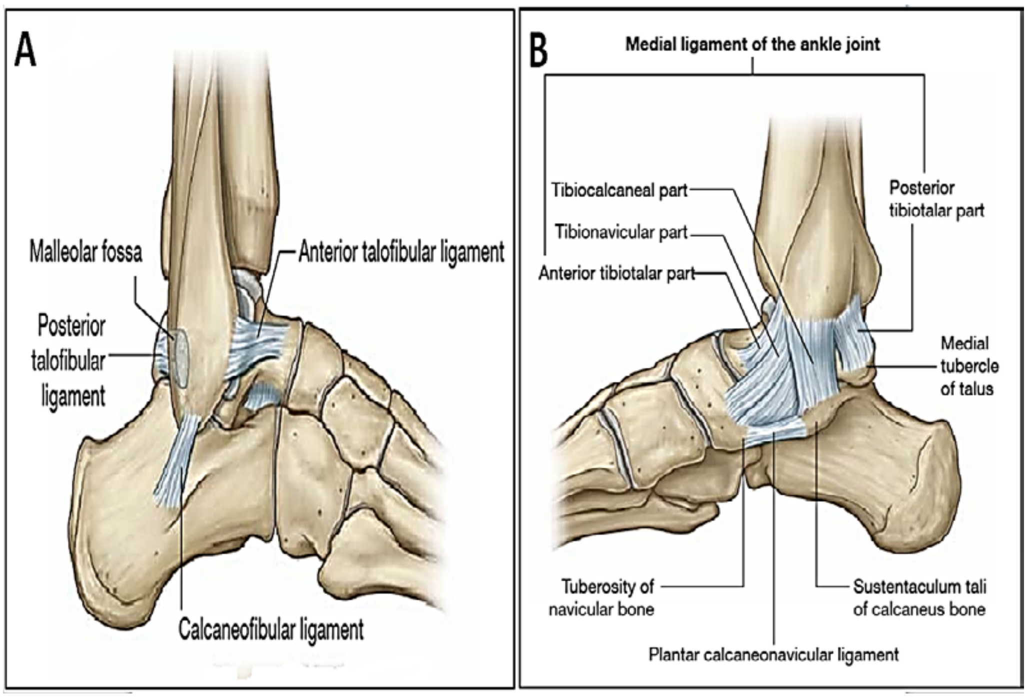

Figure 2.8 Lateral (A) and medial (B) collateral ligaments of the ankle joint (modified from Drake et al., 2010b).

The subtalar (Figure 2.9) joint is a synovial joint between the inferior surface of the talus and upper part of the calcaneus. It is supported by medial, lateral and interosseous talocalcaneal ligaments (Snell, 2008). However, the talocalcaneonavicular joint is a ball and socket joint (Moore et al., 2010) between the anterior parts of the talus and calcaneus and the navicular: it is supported by the spring ligament. Gliding and rotation are possible movements at both the subtalar and talocalcaneonavicular joints (Snell, 2008).

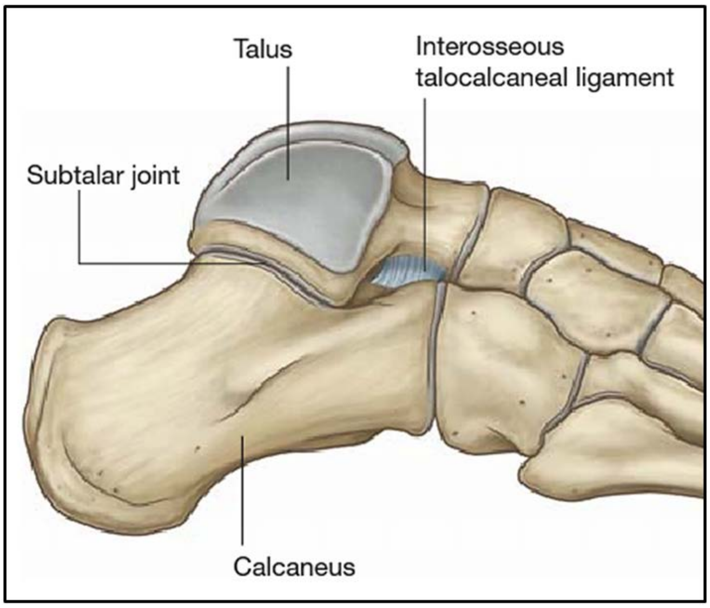

Figure 2.9 The subtalar joint (modified from Drake et al., 2010b).

2.1.3 Spring Ligament

The spring (plantar calcaneonavicular) ligament (Figure 2.10) extends between the sustentaculum tali and the navicular (Drake et al., 2010a). The anterior part of the superficial deltoid ligament connects with its medial border (Standring, 2008a). Previous literature reports that the spring ligament has two or three parts (Tohno et al., 2012; Taniguchi et al., 2003). Taniguchi et al. (2003) state that it is composed of three parts: superomedial, inferior and a third part (Figure 2.11) which was found after removing the fibrocartilaginous surface of the ligament. It passes from the calcaneus between its anterior and middle facets to the tuberosity of the navicular. The spring ligament has a number of functions including transferring weight from the talus, supporting the talar head and longitudinal arch of the foot.

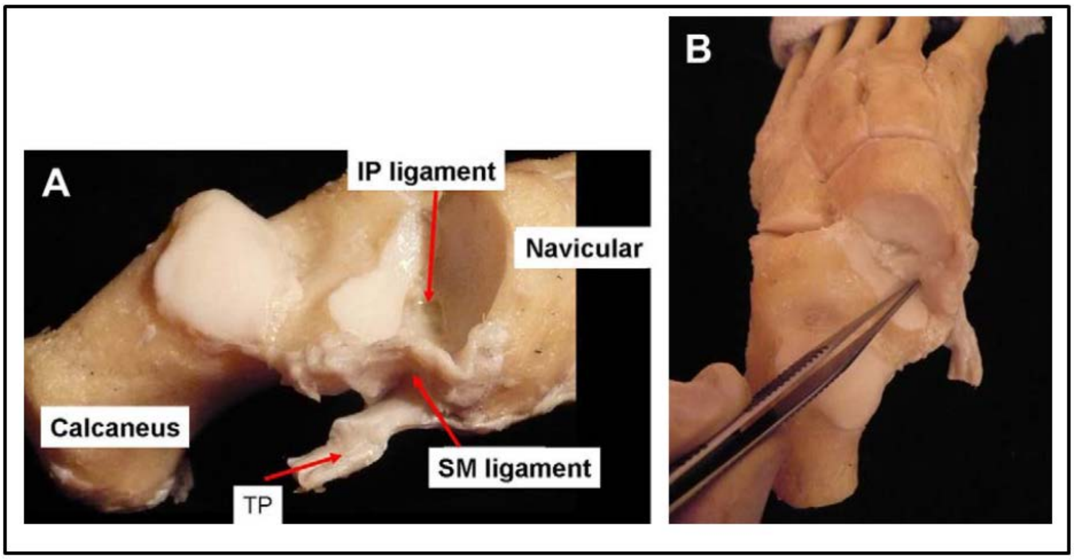

Figure 2.10 Spring ligament (plantar calcaneonavicular): A, dorsal view showing the superomedial part of the ligament (SM) and the inferoplantar part (IP); TP, tendon of the tibialis posterior; B, dorsal view with the clamp pointing toward the inferoplantar part (Vadell and Peratta, 2012).

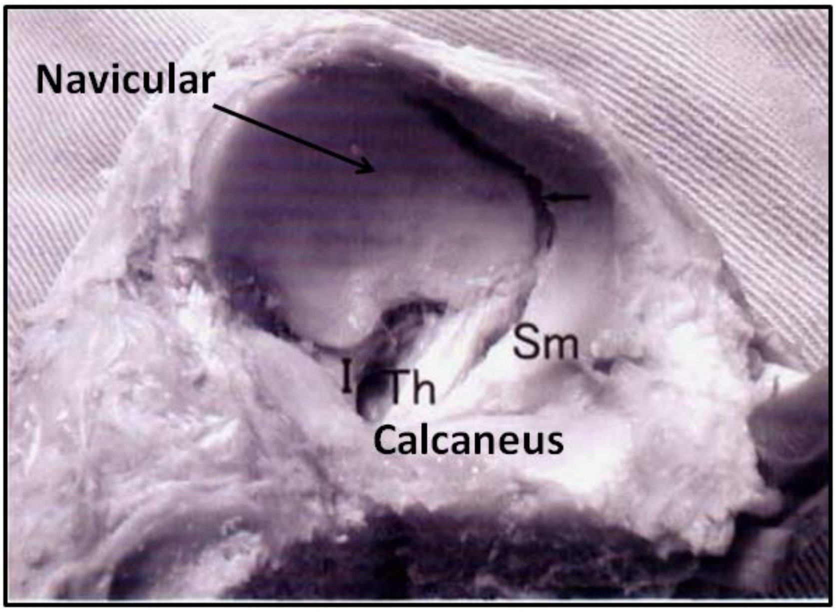

Figure 2.11 Three parts of the spring ligament as described by Tohno et al. (2012) (modified): I, inferior part; Sm, superomedial part; Th, third part.

2.2 Movements and Stability at the Ankle and Subtalar Joints

2.2.1 Axes of Movements at the Ankle and Hindfoot

There are four important axes for movement that take place in the ankle and hindfoot (Figure 2.12). The ankle joint axis is horizontal (Soames, 2003; Kapandji, 1989) (Fig 2.12: z axis) and passes through the lateral and medial malleoli, around which dorsiflexion and plantarflexion (Fig 2.13A) occur in the sagittal plane. Adduction and abduction of the foot in the transverse plane (Fig 2.13C) occur around the vertical long axis of the leg (Fig 2.12: y axis). The horizontal long axis of the foot lies in the sagittal plane (Fig 2.12: x axis), around which supination and pronation (Fig 2.13B) occur (Kapandji, 1989). Finally, inversion and eversion movements occur about the oblique axis of the subtalar joint (Hsu et al., 2008). Three joints, ankle, subtalar and midtarsal, work together with three degrees of freedom, enabling different movements and allowing the foot to maintain equilibrium during walking despite any inconsistencies in the walking surface (Palastanga et al., 2006).

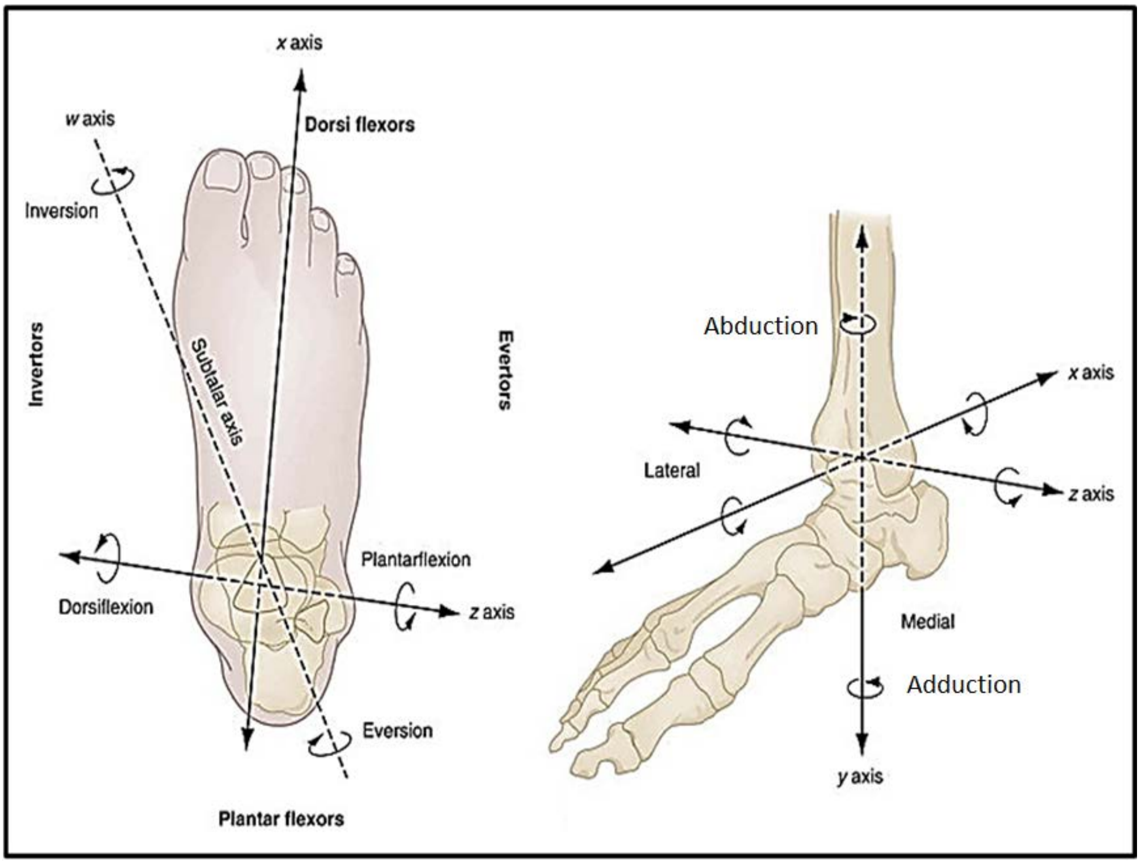

Figure 2.12 Axis of foot movements: z axis, horizontal axis of the ankle; y axis, vertical long axis of the leg; x axis, horizontal long axis of the foot, w axis: oblique subtalar axis (modified from Marx, 2014).

2.2.2 Movements at the Ankle Joint

The ankle is a synovial hinge joint with one degree of freedom: the projection of the line of gravity is anterior to the ankle joint during standing and is continually adjusted to maintain the line within its surface limits. Subtalar and midtarsal joint movements occur in association with those at the ankle joint (Figure 2.13), these being dorsiflexion and plantarflexion (Palastanga et al., 2006). However, there is inconsistency in the literature in naming movements at the ankle (Rasmussen, 1985). For example, Palastanga et al. (2006) and Soames (2003) define extension and flexion at the ankle as dorsiflexion and plantarflexion respectively; while Kreighbaum and Barthels (1996) and Kapandji (1989) considered that dorsiflexion is flexion and plantarflexion extension. Kapandji (1989) stated that dorsiflexion is flexion at the ankle because of the approximation between the foot and the anterior part of the leg while plantarflexion is ankle extension due to movement of the dorsum of the foot away from the leg.

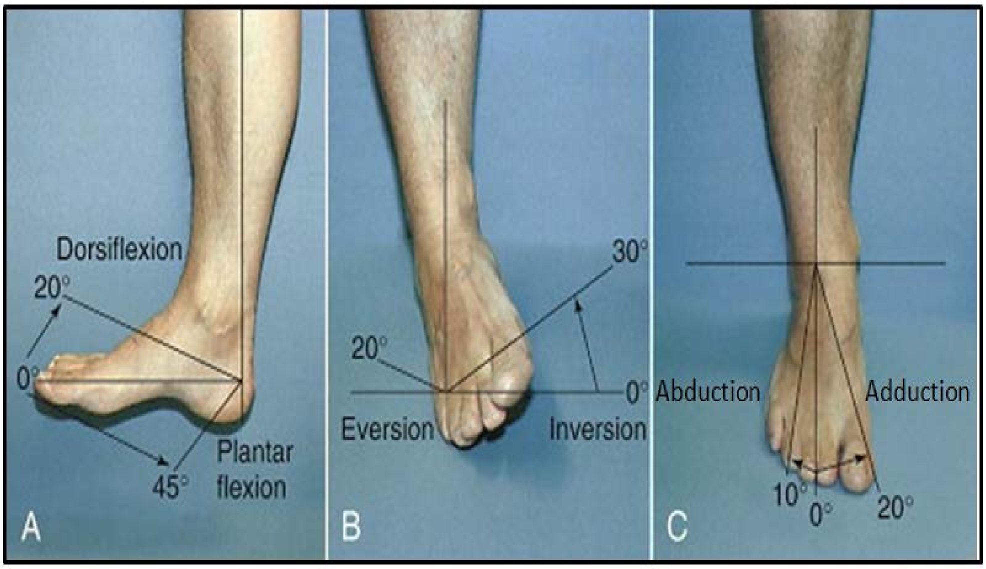

Figure 2.13 Movements at the ankle and subtalar joints: A, dorsiflexion and plantarflexion; B, inversion and eversion; C, abduction and adduction (Ball et al., 2015).

Dorsiflexion is movement of the ankle in the sagittal plane (Rasmussen, 1985) from the neutral position (right angle between foot and leg) with the dorsum of the foot moving upward toward the leg (Palastanga et al., 2006). The ankle is at its maximum level of stability in dorsiflexion (Sarrafian, 1993a). The interosseous and transverse tibiofibular ligaments are tense due to separation of the tibia and fibula, while the anterior part of the talar trochlear surface is pushed towards the posterior part of the tibiofibular mortise (Figure 2.14) (Palastanga et al., 2006). In addition, widening of the ankle mortise results in the lateral malleolus moving 1.4 mm laterally (Kärrholm et al., 1985); and/or the fibula externally rotating (Mulligan, 2011; Close, 1956; Barnett and Napier, 1952). In addition, it has been reported that during dorsiflexion there is internal rotation of the leg (Nordin and Frankel, 2001) or tibia (Close, 1956). Moreover, dorsiflexion is accompanied by talar external rotation (Figure 2.15) (Mulligan, 2011, Bonnel et al., 2010, Norkus and Floyd, 2001) and talar abduction (Bonnel et al., 2010).

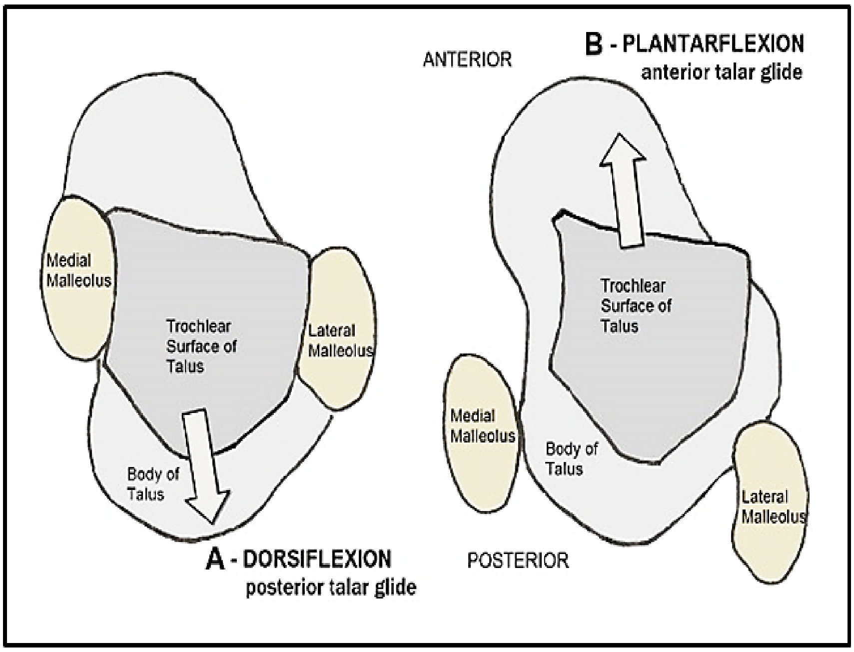

Figure 2.14 Talus gliding anteriorly and posteriorly in plantarflexion and dorsiflexion respectively (Mulligan, 2011).

Dorsiflexion results in tension in the calcaneal tendon, anterior parts of the lateral and medial collateral ligaments as well as the posterior joint capsule (Soames, 2003). The extensor muscles of the leg and their sheaths are connected to the ankle joint capsule and have a role in pulling it forward inhibiting its anterior part from becoming trapped between the talus and tibia in extreme dorsiflexion (Palastanga et al., 2006). Ankle dorsiflexion is checked by the posterior part of the deltoid ligament, the calcaneofibular ligament (CFL), the posterior capsule of the ankle joint, by the talus being wedged between the lateral and medial malleoli and shortening or tension in gastrocnemius and soleus (Palastanga et al., 2006).

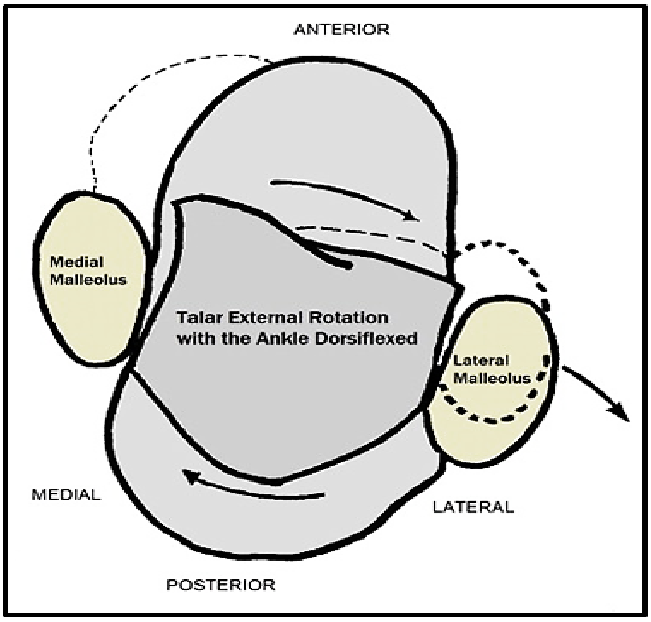

Figure 2.15 External rotation of the talus in dorsiflexion (modified from Mulligan, 2011).

The ankle is least stable in plantarflexion (Palastanga et al., 2006), which occurs when the foot moves downwards and away from the neutral position. Combined with inversion, plantarflexion permits foot adduction and supination (Palastanga et al., 2006). In plantarflexion, talar movements such as rotation (Figure 2.15), abduction and adduction, as well as side to side motion may occur (Figure 2.16). Nordin and Frankel (2001) demonstrated that the leg is externally rotated during plantarflexion; however Bonnel et al. (2010) reported that when the talus is fixed the tibia rotates internally. In plantarflexion, the talus becomes internally rotated (Bonnel et al., 2010, Norkus and Floyd, 2001) or adducted (Bonnel et al., 2010).

Plantarflexion causes tension in the extensor muscles/tendons of the leg, anterior parts of the lateral and medial collateral ligaments and anterior joint capsule, as well as the contact that occurs at maximum plantarflexion between the posterior part of the distal tibia and the posterior talar tubercle (Soames, 2003). In addition, attachment of the PTFL to the fibular sheath (laterally) and the sheath of flexor hallucis longus (medially) play a role in keeping the posterior joint capsule clear of the articulating bones (Palastanga et al., 2006). Plantarflexion is limited by the anterior part of the deltoid ligament, the anterior talofibular ligament (ATFL), the anterior ankle joint capsule, tension in the muscles/tendons of the anterior compartment of the leg (Palastanga et al., 2006) and by the contact between the tibia and posterior aspect of the talus (Valmassy, 1996)

Adduction of the foot occur when the toes move toward the midline, while abduction is the movement away from the midline (Kapandji, 1989; Quiles et al., 1983) the movement occurs in the frontal plane at the tibiotalar part of the ankle mortise (Figure 2.13) (Rasmussen, 1985). Internal and external rotation also occurs at the tibiotalar joint when the foot moves in a horizontal plane medially and laterally respectively (Rasmussen, 1985).

Additional movement includes anterior displacement of the talus, which in normal ankles is between 1.5 mm and 9 mm, while more than 9mm represents the anterior drawer sign when the ATFL is disrupted (Delplace and Castaing, 1975; as cited by Rasmussen, 1985). Moreover, the talar tilt range is used to investigate ankle instability in inversion and plantarflexion. Normal talar tilt in 90.4% of healthy young people (17-20 years old) was 0°, while 7.9% and 1.7% had a tilt angle of 1° – 5° and > 5° with a maximum of 17° being considered normal respectively (Cox and Hewes, 1979). However, Glasgow et al. (1980) suggested that a talar tilt of 6° or more causes instability that would benefit from surgical reconstruction (Figure 2.16).

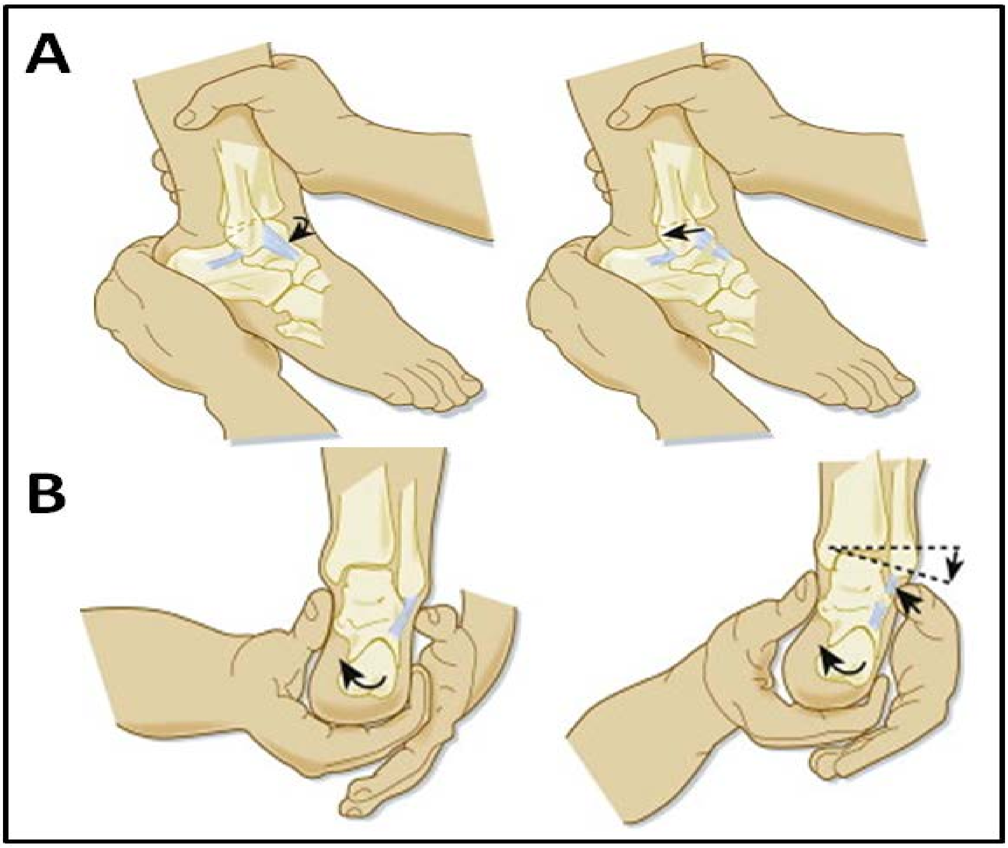

Figure 2.16 A, anterior drawer test to check anterior displacement of the talus and disturbance of the ATFL; B, Talar tilt test to examine side to side movement of the talus (modified from Adams et al., 2013).

Nordin and Frankel (2001) have reported the range of motion (ROM) of dorsiflexion and plantarflexion as 10° - 20° and 40° - 50° respectively (Figure

2.13); while Palastanga et al. (2006) demonstrated the range of motion to be 20° - 30° (dorsiflexion) and 30° - 50° (plantarflexion). The ROM is affected by characteristics of the articular surfaces of the ankle joint, therefore variations will be seen between individuals (Palastanga et al., 2006).

2.2.3 Movements at the Subtalar Joint

The subtalar joint has a complex structure and movement mechanics (Rockar, 1995). The joint has a role in permitting simultaneous motion of the ankle and the knee joints as they both have their joint axes in the horizontal plane (Palastanga et al., 2006). Movement at the subtalar and midtarsal joints should be considered together as it is difficult to exactly distinguish isolated movements (Soames, 2003). In addition, subtalar movement decreases when the ankle is in maximum dorsiflexion or plantarflexion (Leardini et al., 2001).

Inversion (Figure 2.13) results from plantarflexion and external rotation of the tibia, while eversion results from dorsiflexion and internal rotation of the tibia (Nordin and Frankel, 2001). Kapandji (1989) defined inversion as a movement that combines plantarflexion, foot adduction and supination, while eversion consists of dorsiflexion, foot abduction and pronation. The consistency in literature in naming inversion and eversion is variable with supination and pronation in this study, being the definition used by Kapandji (1989). Supination and pronation terminologies is used in some clinical literature to refer to inversion and eversion respectively.

The mean inversion and eversion ROM is 20° and 10° respectively (Swartz, 2014), with inversion causing tension in the fibularis tendons and the plantar, dorsal, lateral, anterior and posterior ligaments, while eversion results in tension in tibialis posterior and the plantar, dorsal and medial ligaments (Soames, 2003). Finally, there is an accessory movement at the subtalar joint which is sliding of the calcaneus anteroinferiorly on the talus (Soames, 2003).

Adduction and abduction at the subtalar joint is the lateral and medial turning of the inferior aspect of the calcaneus respectively, while internal or external rotation is the medial or lateral rotation of the anterior aspect of the calcaneus respectively (Kjærsgaard-Andersen et al., 1989).

Pronation is movement of the sole of the foot laterally (Figure 2.17) (Kapandji, 1989) at the subtalar joint and involves external rotation and forefoot abduction (Rasmussen, 1985). Supination is movement of the sole of the foot medially (Figure 2.17) (Kapandji, 1989) at the subtalar joint involving internal rotation and forefoot adduction (Rasmussen, 1985).

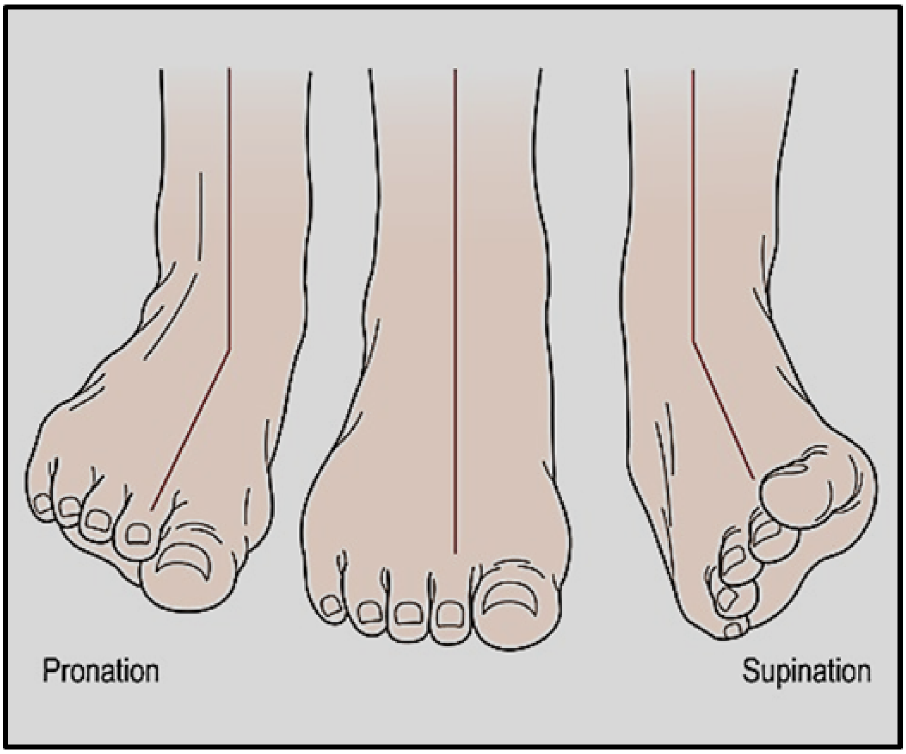

Figure 2.17 Foot Supination and pronation (modified from Palastanga et al., 2006)

Pure pronation without abduction happens when there is medial rotation of the leg at the knee joint, while supination without adduction occurs when there is lateral rotation of the leg. Maximum pronation results in tension in tibialis posterior, the medial collateral ligaments and contact between the calcaneus and floor of the sinus tarsi, while maximum supination causes tension in the lateral, posterior and interosseous ligaments (Soames, 2003). The ROM of supination and pronation is 52° and 25° - 30° respectively (Kapandji, 1989). Movements of the ankle and foot that were considered in the current study, are demonstrated in Table 2.1.

Table 2.1 Movements at ankle and subtalar joints

Movement	**Description**
Dorsiflexion	dorsum of the foot moving upward toward the leg (Palastanga et al., 2006); fibular adduction (Kärrholm et al., 1985) and external rotation (Mulligan, 2011); talar external rotation and abduction (Bonnel et al., 2010)
Plantarflexion	foot moves downwards and away from the neutral position (Palastanga et al., 2006); tibial external rotation (Nordin and Frankel, 2001); talar internal rotation and adduction (Bonnel et al., 2010)
Inversion	combined plantarflexion, foot adduction and supination (Kapandji, 1989)
Eversion	combined dorsiflexion, foot abduction and pronation (Kapandji, 1989)
Adduction	toes movement toward the midline (Kapandji, 1989)
Abduction	toes movement away from the midline (Kapandji, 1989)
Supination	movement of the sole of the foot medially (Kapandji, 1989); internal rotation and forefoot adduction (Rasmussen, 1985)
Pronation	movement of the sole of the foot laterally (Kapandji, 1989); external rotation and forefoot abduction (Rasmussen, 1985)
Varus	movement of the distal part of a limb medially (Martin, 2007)
Valgus	movement of the distal part of a limb laterally (Martin, 2007)

2.2.4 Stability at the Ankle and Subtalar Joints

The ankle joint has a thin fibrous capsule anteriorly and posteriorly compared to the medial and lateral aspects, which are thickened by medial and lateral collateral ligaments (Soames, 2003). The ankle joint is supported by three groups of ligaments: deltoid, lateral collateral ligaments (LCL) and the tibiofibular syndesmotic ligaments (Erickson et al., 1991). The talar and tibial trochlear surfaces are weight-bearing; on the other hand the medial and lateral malleolar surfaces grasp the talar body for stabilisation (Figure 2.14).

Anteroposterior stability of the ankle is controlled by a number of factors including gravity that presses the tibia towards the talus, and the concave shape of the anterior and posterior edges of the tibia which work as bony spurs inhibiting the talus from slipping anteriorly or posteriorly, while the passive stabilising effect of the collateral ligaments and muscles crossing the ankle joint also help in stabilising the ankle (Palastanga et al., 2006).

Ankle ligaments play an important role in stabilising the joint during movement. Consequently, joint integrity is compromised when there is damage or impairment to any of the collateral ligaments of the ankle joint. The ankle joint capsule fuses with the deltoid ligament as well as the anterior and posterior parts of the LCL. Part of the ankle joint capsule is thickened anteriorly and posteriorly to form the anterior and posterior ligaments of the ankle joint: the anterior ligament originates from the inferior part of the tibia and attaches to the talar neck, while the posterior ligament originates from the tibia and fibula and attaches to the posteromedial tubercle (Palastanga et al., 2006).

Posterior deep, anterior and lateral muscles of the leg cross the ankle joint providing support for it and the joints of the foot, as well as the foot arches (Kreighbaum and Barthels, 1996). The fibularis tendons and their sheaths (Rütt and Schmidt, 1993; Sarrafian, 1993a) and tibialis posterior and the long flexor tendons with their fibrous sheaths help in stabilising the ankle joint posterolaterally and posteromedially (Sarrafian, 1993a). The lateral malleolus is considered as a primary restrictor to lateral and anterior talar shifts (Harper, 1987). In addition, the lateral and medial malleoli with the collateral ligaments provide side to side stability of the ankle in non-weight bearing positions (Sarrafian, 1993a).

Stability of the subtalar joint is reinforced mainly by the interosseous ligament as well as the medial and lateral ankle ligaments with attachments to the calcaneus: they help in keeping the talus stable between the malleoli and calcaneus. In addition, active support is achieved by fibularis longus and brevis laterally, as well as flexor hallucis longus, which have a role in stabilising the subtalar joint and preventing the capsule and ligaments being continually strained. The subtalar joint capsule is thickened medially by the medial talocalcaneal ligament, posteriorly by the posterior talocalcaneal ligament, and laterally by the lateral talocalcaneal ligament (LTCL); while the thin anterior aspect of the joint capsule connects with the sinus tarsi, which is an anterolaterally directed tunnel between the talus and calcaneus (Palastanga et al., 2006).

Five talocalcaneal ligaments act to stabilise the subtalar joint, these being the interosseous talocalcaneal, medial talocalcaneal, posterior talocalcaneal, ligamentum cervicis and lateral talocalcaneal ligaments. The interosseous talocalcaneal is a strong ligament consisting of anterior and posterior bands: the deep part of the lateral limb of the inferior extensor retinaculum inserts into the floor of the sinus tarsi between the two bands of the ligament. The medial talocalcaneal ligament passes from the talar posteromedial tubercle to the posterior aspect of the sustentaculum tali. The posterior talocalcaneal ligament is short and runs between the posterolateral tubercle of the talus and superomedial aspect of the calcaneus. The ligamentum cervicis is a strong ligament which becomes taut in inversion: it is situated at the lateral edge of the sinus tarsi between the talar neck and calcaneus (Palastanga et al., 2006).

The lateral talocalcaneal ligament (LTCL) passes posteroinferiorly deep and alongside the CFL from the talar lateral tubercle to the lateral aspect of the calcaneus (Palastanga et al., 2006). Trouilloud et al. (1988) noted that the LTCL was absent in 40% of specimens examined; when it existed, the LTCL either blended with the CFL separating from each other at either the talar or calcaneal insertion, or was distinct from the CFL (as cited by Leardini et al., 2000)

2.2.5 Ankle Joint: Functional Aspects

The ankle joint plays a major role in regulating the foot in the sagittal plane and controlling the line of gravity during standing or body motion (Palastanga et al., 2006). The maximal range of motion (MROM) is the range of motion the joint can reach without jeopardizing the ligaments. The functional range of motion (FROM) is the required range of motion during functional activities such as running or walking (Kleipool and Blankevoort, 2010). The required ankle ROM to perform normal activities varies based on the nature of the activity: gait on a normal surface (15° dorsiflexion, 20° plantarflexion), ascending stairs (25° dorsiflexion, 30° plantarflexion), descending stairs (30° dorsiflexion and 30° plantarflexion), putting on shoes (25° plantarflexion) and tying shoes laces (15° dorsiflexion) (Soames, 2003). However, Nordin and Frankel (2001) reported the dorsiflexion and plantarflexion ROM required for normal walking to be 10.2° and 14.2° respectively. Increasing walking speed leads to a decrease in ankle motion, especially in plantarflexion (Palastanga et al., 2006).

During walking, the gait cycle is composed of two phases (Figure 2.18), the stance and swing phases. The stance phase comprises 62% of the gait cycle and consists of heel strike, foot flat, heel rise, push off and toe off; while the swing phase comprises 38% of the gait cycle and consists of acceleration, toe clearance and deceleration. In heel strike and foot flat, eversion occurs enabling the forefoot to be flexible to absorb shock and to accommodate to different surfaces. In mid stance and push off, inversion results in the foot becoming rigid and therefore able to give the necessary force to push off. Modest plantarflexion occurs at heel strike and increases until reaching flat foot, then dorsiflexion starts at mid stance; plantarflexion and dorsiflexion occur at toe off and mid swing respectively (Nordin and Frankel, 2001).

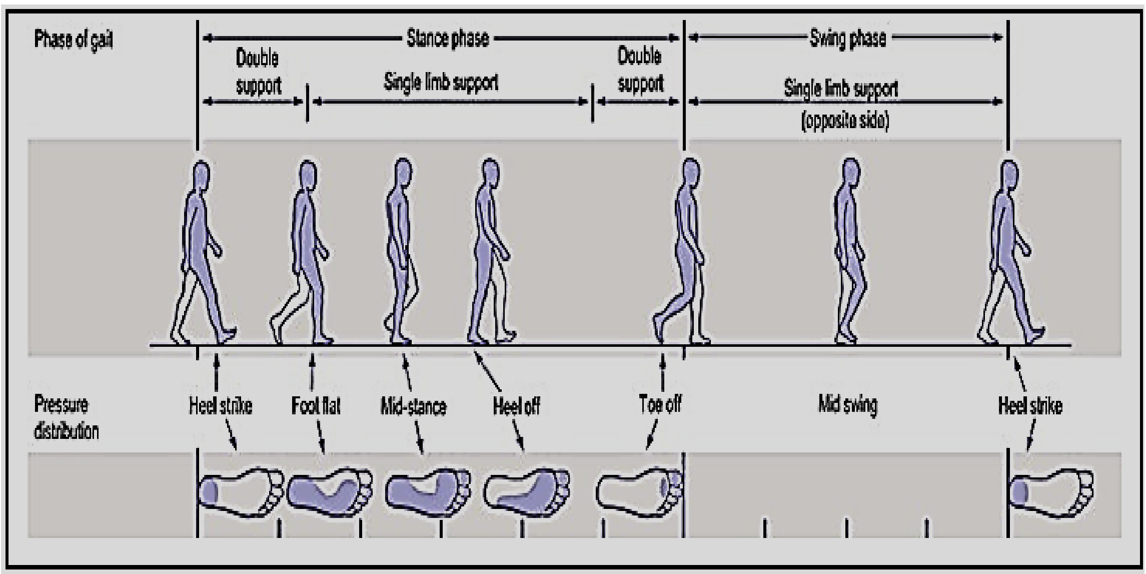

Figure 2.18 Gait phases (Standring, 2008b).

2.3 Anatomy of the Anterior Talofibular Ligament (ATFL)

2.3.1 Band Number of the Anterior Talofibular Ligament (ATFL)

Previous studies do not agree on the number of the ATFL bands, with Golano et al. (2010) reporting that previous studies give different descriptions of the number of the bands, being between one and three. The literature gives five descriptions for the number of ATFL bands. Some studies have reported the ATFL to have one (Figure 2.19) or two bands (Figure 2.20) (Rein et al., 2015; Clanton et al., 2014; Neuschwander et al., 2013; Yıldız and Yalcın, 2013; Raheem and O'Brien, 2011; Taser et al., 2006; Burks and Morgan, 1994; Wiersma and Griffioen, 1992).

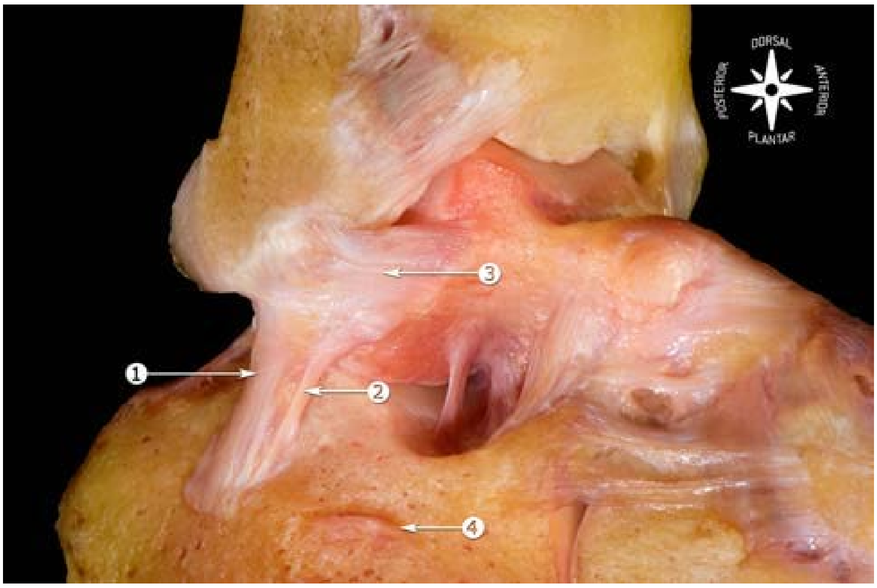

Figure 2.19 Anterior talofibular ligament (Golanó et al., 2010): 1, calcaneofibular ligament (CFL); 2, lateral talocalcaneal ligament (LTCL); 3, anterior talofibular ligament (ATFL); 4, Fibular tubercle of the calcaneus.

Three studies have observed one, two and three band forms of the ATFL (Boonthathip et al., 2011; Uğurlu et al., 2010; Milner and Soames, 1997). Other studies report that the ATFL always has a single band (Wenny et al., 2014) or two bands (Sindel et al., 1998), while Sarrafian (1993a) states that the ATFL only exists in either the two or three band form. Rein et al. (2015) observed the single band form in 70% and the bifurcate form in 30% of specimens, the two distinctive bands being separated from each other proximally and distally. Wiersma and Griffioen (1992) also found one (68%) and two (32%) independent bands, while Clanton (2014) observed the one and two band forms equally. Neuschwander et al. (2013) reported the ATFL (n= 8) as having two bands with two talar footprints in six feet and one band in two feet. Yıldız and Yalcın (2013) observed the ATFL in one or two band forms in 75.6% and 24.4% respectively, while Raheem and O'Brien (2011) observed one band in 14 feet and two bands in 5 feet. In another study, the single and bifuracte ATFL were reported in 97.6% and 2.4% of specimens respectively (Taser et al., 2006). What is clear in these studies is that the single band form was observed more often than the two band form.

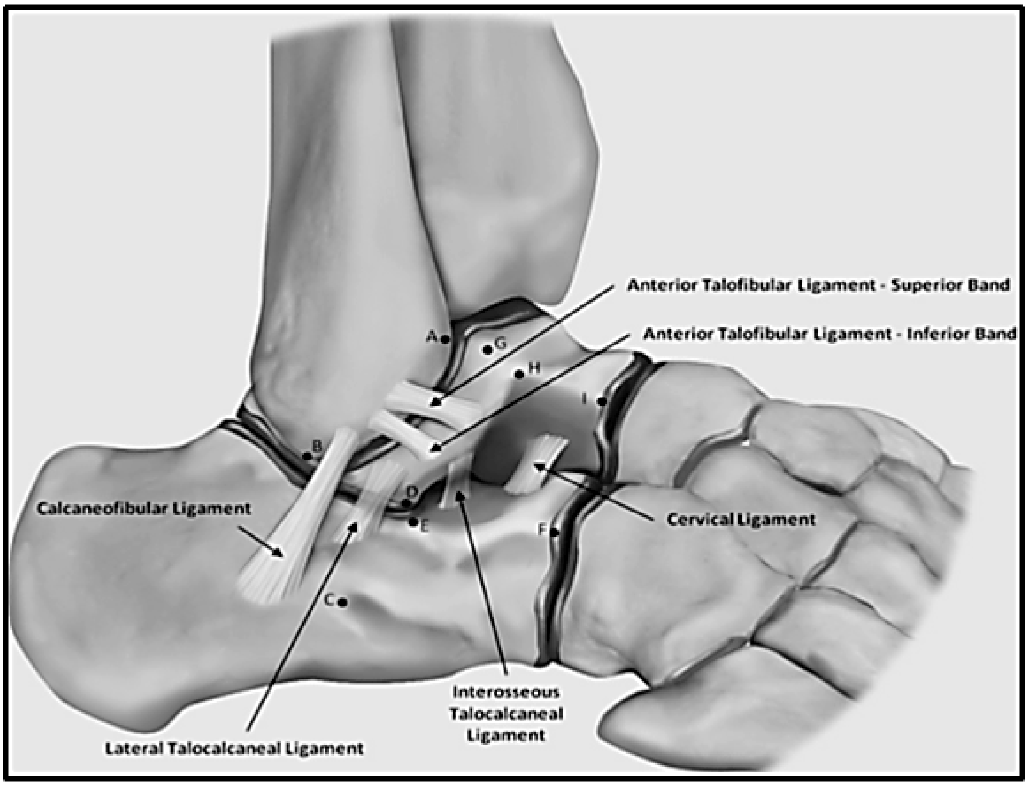

Figure 2.20 Bifurcate form of the ATFL: A; anterior fibular tubercle, B; lateral malleolar tip, C; posterior edge of the fibular tubercle, D; lateral talar process tip, E; articular surface of the calcaneus, F; calcaneocuboid joint line, G; anterolateral corner of trochlea, H; proximal edge of the neck of the talus, I; distal edge of the neck of the talus (modified from Clanton et al., 2014).

2.3.2 Proximal Attachment of the Anterior Talofibular Ligament (ATFL)

The ATFL originates from the anterior border of the lateral malleolus (Taser et al., 2006; Hua et al., 2008; Clanton et al., 2014), anterosuperior to the lateral malleolar tip (Kumai et al., 2002). However, there may be fibres connecting to the CFL near its origin to the inferior band of the ATFL as observed in dissected formalin embalmed specimens (Apoorva et al., 2014). Sarrafian (1993a) also observed that the ATFL and CFL origins were united in many specimens. Studies by Taser et al. (2006), Sindel et al. (1998) and Burks and Morgan (1994) report the distance between the ATFL middle proximal attachment and the tip of the lateral malleolus to be 13.32 ± 1.17 mm, 10 ± 1.3 mm and 10 mm respectively. Moreover, Wenny et al. (2014) reported the distance between the ATFL mid proximal insertion and the lateral malleolar tip in dissected specimens that were formalin embalmed as 0.58 ±1.89 mm; while the distance between the ATFL mid fibular insertion and the anterior border of the lateral malleolus was 3.45±1.34 mm. Clanton et al. (2014) examined the origin of the single ATFL band in fresh frozen specimens, and found it was 13.8 mm from the lateral malleolar tip, inserting 49.8% of the distance between the lateral malleolar tip and the anterior fibular tubercle and had a fibular footprint of 56.8 mm^2. They also found that the superior and inferior bands in the bifurcate form (Figure 2.21) originated 16.3 mm and 10.2 mm from the lateral malleolar tip respectively, and had fibular foot print areas of 38.4 mm^2 and 29.4 mm^2 respectively.

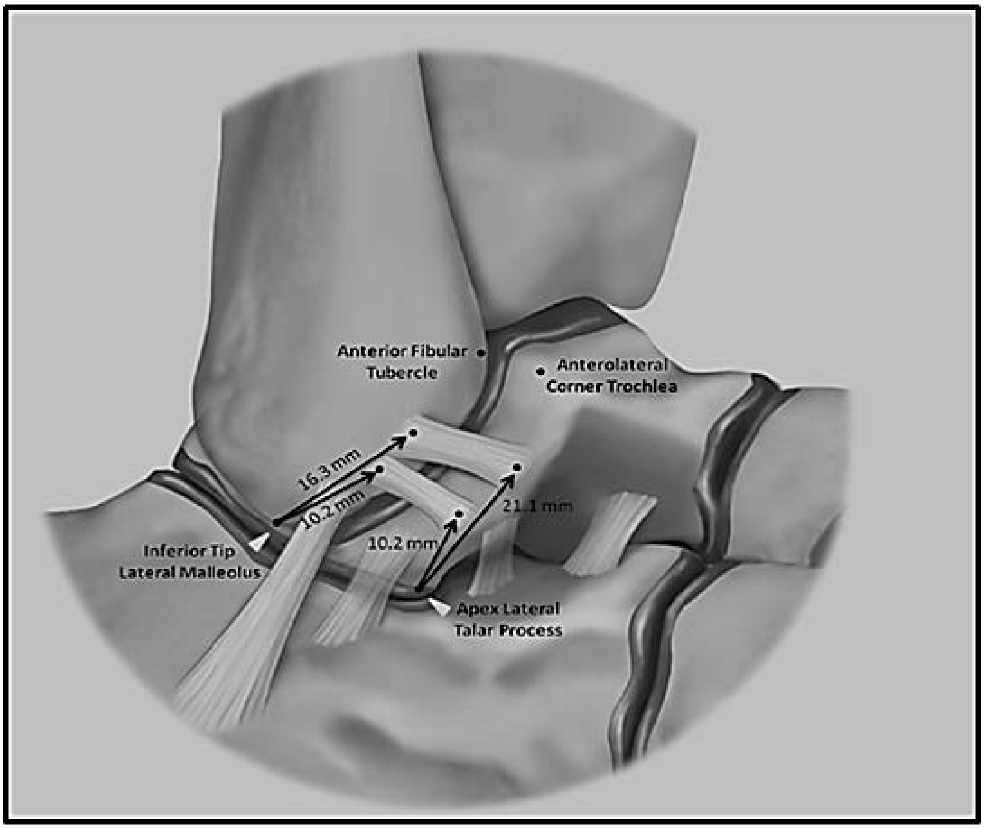

Figure 2.21 Distance between the superior and inferior bands of the ATFL bifurcate form and the lateral malleolar tip (Clanton et al., 2014).

An MRI study that was carried out on living individuals by Dimmick et al. (2008) reported the distance between ATFL proximal insertion and tip of the lateral malleolus to range between 3 and 6 mm, with two cases being 9 and 14 mm. Wenny et al. (2014) reported the ATFL fibular attachment area was 0.36 ± 0.09 cm^2. Neuschwander et al. (2013) examining the origin of the ATFL in 8 dissected frozen feet and analysed using CT scans and 3D analysis reported the ATFL and CFL fibular footprint surface area to be 3.48 ± 0.39 cm^2.

The proximal/distal dimension for the bony attachment of the ATFL fibular attachment has been stated as 8.2 mm in frozen (Burks and Morgan, 1994) and 7.5 ± 1.32 mm (Sindel et al., 1998) in embalmed ankle specimens. The medial/lateral dimension of the ATFL proximal insertion reported by Burks and

Morgan (1994) and Sindel et al. (1998) was 5.4 mm and 5.4 ± 0.8 mm respectively.

Two studies examined formalin embalmed specimens; Uğurlu et al. (2010) stated that the angle between the ATFL and CFL in the neutral ankle position was 113°, while Yıldız and Yalcın (2013) reported this angle as 112° ± 14° in right feet and 106° ± 19° in left feet. Moreover, the angle between the ATFL and anterior inferior tibiofibular ligament was 68° (Uğurlu et al., 2010). The ATFL is anteriorly, inferiorly and medially oriented in the neutral position (Luo et al., 1997).

2.3.3 Distal Attachment of the Anterior Talofibular Ligament (ATFL)

Previous studies disagree about the distal insertion of the anterior talofibular ligament, with some reporting the distal insertion to be on the neck of the talus (Palastanga et al., 2006; Milner and Soames, 1997; Wiersma and Griffioen, 1992), specifically into the lateral aspect of the talar neck (Sindel et al., 1998), while others (Hua et al., 2008: Kumai et al., 2002) give the insertion to a facet on the talus lateral to the talar neck and the anterior edge of the lateral talar articular surface. Boonthathip et al. (2011) and Sarrafian (1993a) observed the ATFL talar insertion to be to the body of the talus, while the distal insertion was at the junction between the talar body and neck (Neuschwander et al., 2013). Uğurlu et al. (2010) found that one band of the three band form had the inferior band inserting onto the calcaneus.

The distance between the ATFL mid distal insertion to the subtalar joint was 18 mm (Burks and Morgan 1994) and 14.2 ± 1.78 mm (Sindel et al., 1998), while the distance between the ATFL talar attachment and the superior and inferior surfaces of the talar body were 14.77 ± 2.24 mm and 17.03 ± 1.5 mm (Taser et al., 2006). The distance between the mid distal insertion of the superior band of ATFL (SATFL) and the inferior band of ATFL (IATFL) was 11.5 ± 1.0 mm (Neuschwander et al., 2013).

Clanton et al. (2014) examined the ATFL talar attachment and reported that a single ATFL inserted distally 17.8 mm to the apex of the lateral talar process some 81.8% of the distance between the lateral talar process and anterolateral corner of the trochlea. In the two band form of ATFL the ligament inserted distally 21.1 mm (SATFL) and 10.2 mm (IATFL) to the apex of the lateral talar process, some 65.7% (SATFL) and 33.7% (IATFL) of the distance between the lateral talar process and anterolateral corner of the trochlea (Clanton et al., 2014).

The ATFL proximal/distal talar attachment was 8.7 mm (Burks and Morgan 1994) and 6 ± 0.99 mm (Sindel et al., 1998), while the medial/ lateral talar attachment was 5.6 mm (Burks and Morgan 1994) and 4.9 ± 1.12 mm (Sindel et al., 1998). The single form of the ATFL had a talar footprint area of 60.7 mm^2 (Clanton et al., 2014) and 48 ± 11 mm^2 (Wenny et al., 2014). The superior band of the ATFL (SATFL) in the 2 band form had a distal attachment area of 47 mm^2 (Clanton et al., 2014) and 150 ± 26.00 mm^2 (Neuschwander et al., 2013) (Figure 2.22). The inferior band of the ATFL (IATFL) in the 2 band form had a distal attachment area of 42 mm^2 (Clanton et al., 2014) and 90.0 ± 7.00 mm^2

(Neuschwander et al., 2013). The ATFL inserting to the talus articular cartilage that contains fibrocartilage that may resist compression (Kumai et al., 2002).

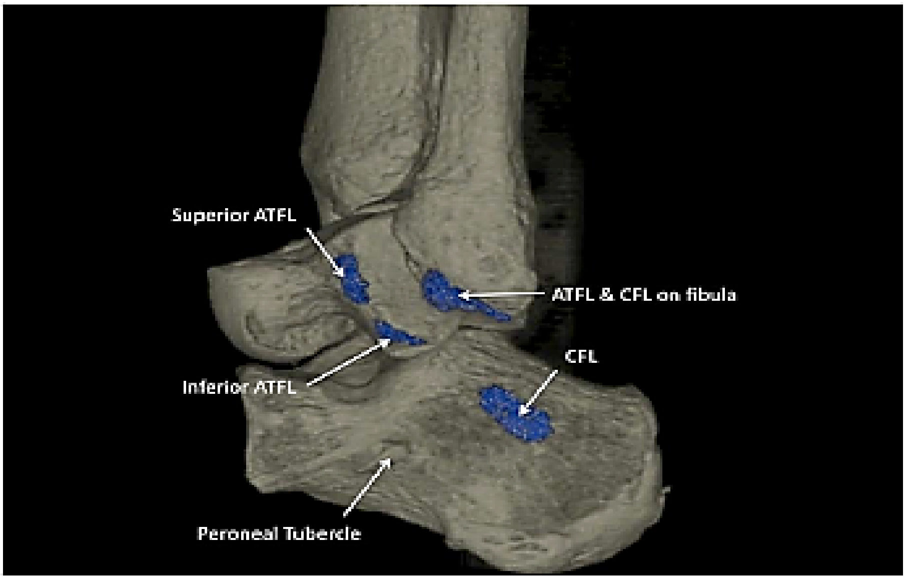

Figure 2.22 Superior band (SATFL) and inferior band (IATFL) of ATFL footprints on the talus (Neuschwander et al., 2013).

2.3.4 Anterior Talofibular Ligament (ATFL) Dimensions

ATFL dimensions (Table 2.2) have been investigated in a number of studies, with the literature showing discrepancies in the length, width and thickness. Direct measurements were reported in a number of a dissection based studies, with length ranging between 11.38 mm and 24.8 mm (Table 2.2). Burks and Morgan (1994) consider the ATFL to be the main band and measured it as the ATFL unless an additional band was observed.

Table 2.2 Dimensions of the anterior talofibular ligament (ATFL): NK; not known, DF; dorsiflexion, PF, plantarflexion.

Study	N	Study mode/ specimens	Length (mm)	Width (mm)	Thickness (mm)
Ruth, 1961	75	30 Dissected specimens/ 45 surgical operation	12	5	
Siegler et al., 1988	20	Dissection/ frozen	17.81 ± 3.05		
Buzzi et al., 1993	10	Dissection/ formalin embalmed	17.5	10.8	
Sarrafian, 1993a	NK	NK/ NK	15	8	2
Burks and Morgan, 1994	39	Dissection/ 30 frozen, 9 embalmed	ATFL: 24.8 IATFL : 21	ATFL: 7.2 IATFL: 4.6	
Luo et al., 1997	11	Dissection/ NK	11.5 ± 2.5		
Ahmad et al., 1998	19	MRI/ living individuals			3
Milner and Soames, 1998a	40	Dissection/ NK	13 ± 3.9	11 ± 3.3	
Sindel et al., 1998	24	Dissection/ NK	ATFL 19.1 ± 2.28 IATFL: 15.2 ± 2.62	ATFL: 6.7 ± 1.06 IATFL: 4.5 ± 1.09	
Ozeki et al., 2002	12	Dissection/ fresh frozen	19.8 ± 1.92		
Butler and Walsh, 2004	8	Dissection/ fresh frozen			1.8 ± 0.6
McDermott et al., 2004	20	MRI and Dissection/ fresh ambuted	Direct measurement: 19 ± 9.4 MRI: 15±2.85		
Mkandawire et al., 2005	5	Dissection/ fresh unembalmed	18.89 ± 2.97		
Taser et al., 2006	42	Dissection/ unknown embalming	22.37 ± 2.5	Proximal: 10.77 ± 1.56 Middle: 6.75 ± 2.89 Distal: 10.96 ± 2.38	
Dimmick et al., 2008	28	MRI/ living individuals			2.19 ± 0.6 men: 2.44 ± 0.49 women: 2.16 ± 0.47
Hua et al., 2008	30	MRI/ living individuals			1.46 ± 0.21
De Asla et al., 2009	4	MRI and dual-orthogonal fluroscopy/	Neutral: 16.3 ± 3 Maximal DF: 13.9 ± 2.9 Maximal PF:		

Study	N	Study mode/ specimens	Length (mm)	Width (mm)	Thickness (mm)
		living individuals	20.8 ± 2.7 Maximal supination: 17.4 ± 3 Maximal pronation: 14.8 ± 2.5		
Uğurlu et al., 2010	22	Dissection/ formalin embalmed	14.38 - 20.84 Single band: 20.84 2 bands: ATFL: 18.74, IATFL: 15.33 3 bands: ATFL: 14.38, MATFL: 14.46, IATFL: 16.12	7.61 - 12.98 Single band: 7.61 2 bands: ATFL: 5.39, IATFL: 4.92, 3 bands: ATFL: 4.06, MATFL: 4.44, IATFL: 4.48	
Boonthathip et al., 2011	10	MRI/ frozen	21.2 ± 5.6	4.4 ± 1	
Raheem and O'Brien, 2011	20	Dissection/ unknown embalming	neutral: 15.5 ± 7.7 dorsiflexion: 14.5 ± 6.3 plantarflexion: 18 ± 9.8 mm	10 ± 7	
Neuschwander et al., 2013	8	Dissection/ frozen	ATFL: 19.7 ± 1.2 IATFL: 16.7 ± 1.1		
Yıldız and Yalcın, 2013	46	Dissection/ formalin embalmed	Shortest length: 12.24 ± 1.99 Longest length: 14.19 ± 2.02	11.07 ± 5.63	
Choo et al. (2014)	33	MRI/ living individuals		Single: 5.5 Two bands: SATFL: 5.1 IATFL: 2.5 Three band: SATFL: 3 MATFL: 2.1 IATFL: 2.1	Single: 2.3 Two bands: SATFL: 1.9 IATFL: 1 Three band: SATFL: 1.4 MATFL: 1.5 IATFL: 1.4
Wenny et al., 2014	17	Dissection/ formalin embalmed	proximal/ posterior length: 12.85 ± 2.64 ATFL plantar/ anterior length: 11.38 ± 2.25	Talar/calcaneal width: 6.62 ± 1.39 Fibular/tibial width: 6.5 ± 1.51	
Haytmanek et al., 2015	11	Radiography (miniature fluoroscopy)/ fresh frozen	lateral view: 9.4 ± 2.4 mortise view: 12.6 ± 1.8		

ATFL length measured using radiography ranged between 9.4 mm and 20.8 mm (Haytmanek et al., 2015, McDermott et al, 2004, Boonthathip et al., 2011, De Asla et al., 2009). De Asla et al. (2009) examined four normal ankles using MRI and dual-orthogonal fluroscopy in different joint positions.: ATFL length was 16.3 ± 3 mm (neutral), 13.9 ± 2.9 mm (maximal dorsiflexion), 20.8 ± 2.7 mm (maximal plantarflexion), 17.4 ± 3 mm (maximal supination) 14.8 ± 2.5 mm (maximal pronation), indicating that the ATFL was most taut and vulnerable to injury in plantarflexion and supination. Therefore, grafts used in reconstruction procedures should be tensioned in different joint positions in order to retrieve the potential function.

ATFL width ranged between 4.06 mm and 12.98 mm (Table 2.2). Yıldız and Yalcın (2013) observed that ATFL width was wider in right feet (9.07 mm) compared to left feet (8.07 mm): the SATFL was wider in left feet (6.57 mm) compared to right feet (4.9 mm), while the IATFL was wider in right feet (4.65 mm) compared to left feet (3.36 mm).It has been reported that there is no change in width in the different joint positions including neutral, dorsiflexion and plantarflexion (Raheem and O'Brien, 2011).

None of the earlier studies investigating ATFL dimensions directly measured its thickness; although Sarrafian (1993a) did state thickness as 2 mm. Radiographic based studies have determined ATFL thickness between 1.46 mm and 2.44 mm.

2.4 Anatomy of the Calcaneofibular Ligament (CFL)

The calcaneofibular ligament (CFL) is cord-like, extending between the lateral malleolus of the fibula and lateral surface of the calcaneus (Figure 2.23), being oriented posteroinferomedially (Luo et al., 1997; Kitsoulis et al., 2011) in the neutral position (Boonthathip et al., 2011; Taser et al., 2006). The tendons of the fibularis muscles and their sheath may leave an impression on the CFL as they cross and cover most of the ligament, leaving 1 cm visible (Sarrafian, 1993a). Dowling et al. (2003) also reported that the tendon of fibularis brevis has an attachment to the lateral part of the ankle joint, with 7 of 8 dissected specimens having the fibularis brevis tendon attached to the CFL. In most of the literature the CFL has one band (Raheem and O'Brien, 2011; Golano et al., 2010; van den Bekerom et al., 2008; Milner and Soames, 1998a): though Apoorva et al. (2014) have reported CFL fasciculation. Kitsoulis et al. (2011) found one band in 72.2% of specimens, two bands in 22.2% and a third band in 5.6% of specimens.

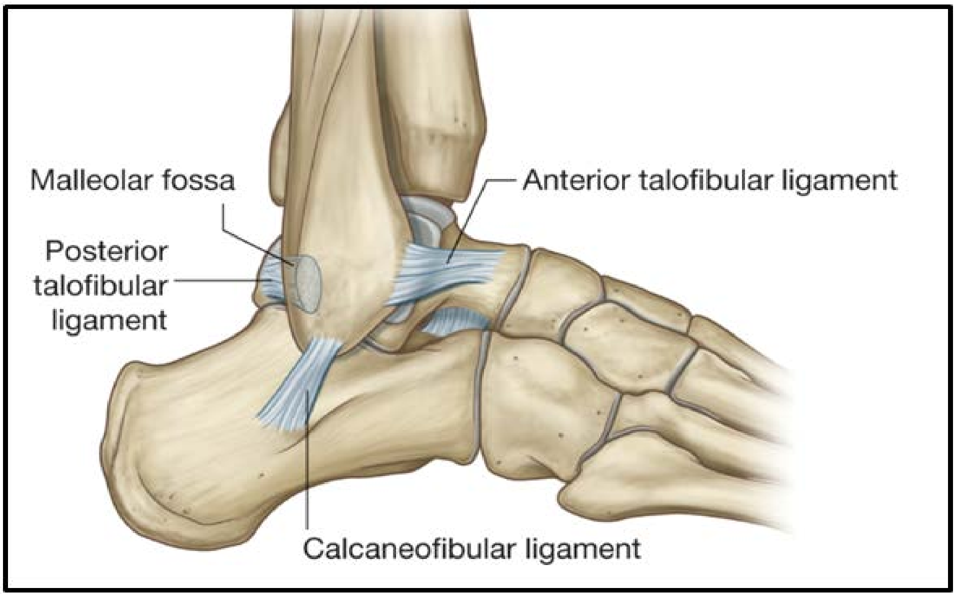

Figure 2.23 The calcaneofibular ligament (CFL) (Drake et al., 2010b).

2.4.1 Proximal Attachment of the Calcaneofibular Ligament (CFL)

The calcaneofibular ligament (CFL) originates (Figure 2.24) proximally below the origin of the ATFL (Clanton et al., 2014), from the lower part of the anterior border of the lateral malleolus of the fibula (Kitsoulis et al., 2011). Hua et al. (2008) report the CFL originating proximally below the lateral malleolar tip, while Sarrafian (1993a) state that the CFL origin did not extend to the tip of the lateral malleolus: Wiersma and Griffioen (1992) are of the view that the lateral malleolar tip has no ligamentous attachments. Buzzi et al. (1993) reported that the CFL originates anterior to the lateral malleolar tip extending to the malleolar fossa: it may blend with LTCL, being superficial to it. However, a number of studies have reported that in some specimens there was blending of the proximal attachments of the ATFL and CFL (Apoorva et al., 2014; Burks and Morgan, 1994; Sarrafian, 1993; Wiersma and Griffioen, 1992). In addition, there may be fibres connecting the CFL near its origin to the inferior band of the ATFL

(Apoorva et al., 2014). Wiersma and Griffioen (1992) observed that in 83% of specimens a bridge was formed by the LTCL passing between ATFL and CFL.

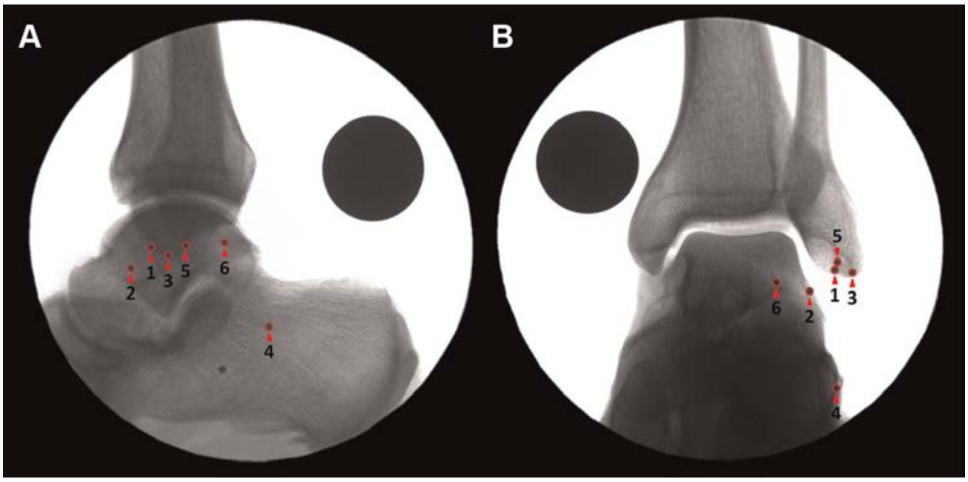

Figure 2.24 Radiograph of the ankle joint in (A) lateral and (B) mortise views: (1) ATFL proximal attachment; (2) ATFL distal attachment; (3) CFL proximal attachment; (4) CFL distal attachment; (5) PTFL proximal attachment; (6) PTFL distal attachment (Haytmanek et al., 2015).

Previous studies have reported the distance between the CFL mid proximal fibular insertion and the lateral malleolar tip as 7.3 ± 1.49 mm (Sindel et al., 1998) and 8.5 mm (Burks and Morgan, 1994). Clanton et al. (2014) reported the distance between the malleolar tip and CFL origin as 5.3 mm (Figure 2.25), with the CFL inserting proximally 16.2% of the distance between the lateral malleolar tip and anterior fibular tubercle, having a fibular footprint (attachment) area of 29.8 mm^2 (Clanton et al., 2014) and 25 ± 11 mm^2 (Wenny et al., 2014). Neuschwander et al. (2013) reported a total fibular footprint area for the ATFL and CFL of 34.8 ± 3.9 mm^2. The proximal/distal dimensions of the CFL fibular attachment were 6.8 ± 1.4 mm (Sindel et al., 1998) and 8.2 mm (Burks and Morgan, 1994), while the medial/lateral dimension of the CFL fibular insertion was 5.7 ± 1.06 mm (Sindel et al., 1998) and 6.2 mm (Burks and Morgan, 1994).

The angle between the ATFL and CFL was 113°, while the angle with the IATFL was 134° (Ugurlu et al., 2010).

Raheem and O'Brien (2011) examined the angle between the ATFL and CFL along their lengths reporting it as 13° ± 6°, 13° ± 6° and 12° in dorsiflexion, plantarflexion and neutral respectively. However, the angle between the CFL and fibula in dissection based measurements and radiographic measurements was 133° and 129° respectively (Burks and Morgan, 1994), while the angle with the sagittal plane was 52° (Kitsoulis et al., 2011). It has been demonstrated that the CFL is oriented inferiorly, posteriorly and medially in the neutral position (Boonthathip et al., 2011; Taser et al., 2006; Luo et al., 1997).

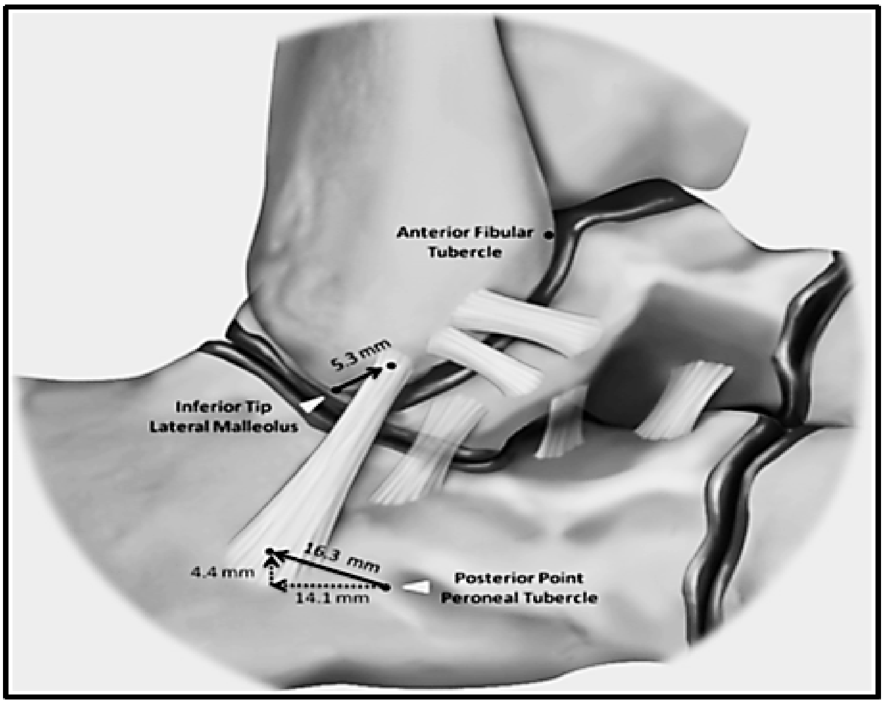

Figure 2.25 The distance between the CFL proximal attachment and the lateral malleolar tip, as well as between the CFL distal attachment and the posterior part of the fibular tubercle (modified from Clanton et al., 2014).

2.4.2 Distal Attachment of the Calcaneofibular Ligament (CFL)

The CFL inserts distally to the calcaneus (Hua et al., 2008) on its lateral surface (Sarrafian, 1993a), attached to a tubercle (tuberculum ligamenti calcaneo fibularis) (Clanton et al., 2014; Taser et al., 2006) posterosuperior to the peronei processus trochlearis (fibular tubercle) (Palastanga et al., 2006; Taser et al., 2006; Sarrafian, 1993a) or posterosuperior to the posterior part of the fibular process (Clanton et al., 2014). However, surgeons may not know the exact insertion of the calcaneofibular ligament during a reconstruction procedure (Burks and Morgan, 1994). Yıldız and Yalcın (2013) reported that the CFL calcaneal attachment cannot be exactly located due to the way the CFL spreads onto the calcaneus. In addition, it is variable in direction, shape and size, with the shape of the ligament varying from cord-like to a fan-shaped structure spreading and attaching distally to the calcaneus (Figure 2.26) (Ruth, 1961).

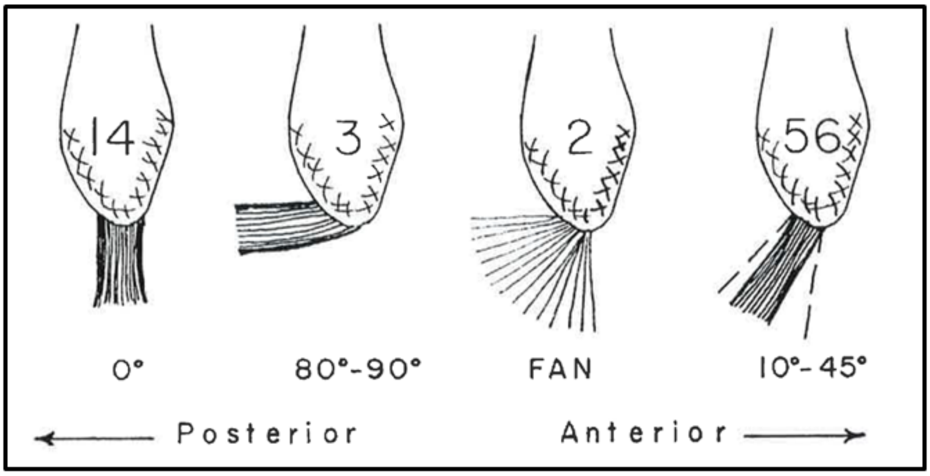

Figure 2.26 Variables shape of the CFL observed in a number of specimens observed by Ruth, (1961).

The distance between the CFL calcaneal footprint and the fibular tubercle of the calcaneus was 27.1 ± 1.0 mm (Neuschwander et al., 2013) (Figure 2.27) and 16.3 mm (Figure 2.25) (Clanton et al., 2014). Moreover, the CFL mid-distal attachment from the subtalar joint was 12.8 ± 1.61 mm (Sindel et al., 1998) and 13 mm (Burks and Morgan, 1994).

The proximal/distal dimension of the CFL calcaneal attachment was 7.7 ± 1.15 mm (Sindel et al., 1998) and 10 mm (Burks and Morgan, 1994), while the medial/lateral dimension of the distal attachment was 7 ± 1.1 mm (Sindel et al., 1998) and 8.2 mm (Burks and Morgan, 1994). Moreover, the CFL had a calcaneal footprint area of 2.68 ± 02 cm^2 (Neuschwander et al., 2013) and 1.23 ± 0.24 cm^2 (Wenny et al., 2014).

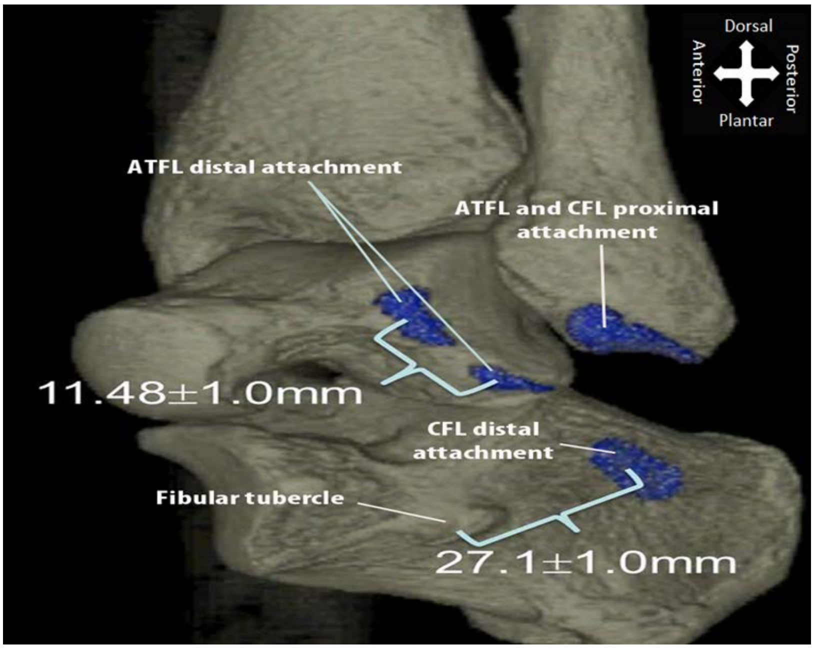

Figure 2.27 The distance between the CFL distal attachment and the calcaneal fibular tubercle, which in this specimen is 27.1 ± 1.0 mm (modified from Neuschwander et al., 2013).

2.4.3 Calcaneofibular (CFL) Dimensions

Several groups have measured the length of the calcaneofibular ligament showing large differences (Table 2.3) ranging between 15.21 mm and 40 mm. MRI studies have also investigated the length of the CFL, being reported as 31 ± 6 mm (Boonthathip et al., 2011). De Asla et al. (2009), using MRI and dual-orthogonal fluroscopy on four normal ankles, studied the length of the CFL under different conditions (Table 2.3).The width of the CFL ranged between 4 and 7.6 mm (Table 2.3).

CFL thickness was 1.58 mm (Kitsoulis et al., 2011), 1.65 ± 0.43 mm (Apoorva et al., 2014) and 3 mm (Sarrafian, 1993a); however MRI studies report the thickness as 3 mm (Ahmad et al., 1998), 2.13 ± 0.5 mm (Dimmick et al., 2008) and 1.52 ± 0.21 mm (Hua et al., 2008). Furthermore, Hua et al. (2008) reported CFL thickness in normal and injured ankles as 1.52 ± 0.21 mm and 2.32 ± 0.17 mm, while Dimmick et al. (2008) observed the thickness in men as 2.28±0.53 mm (normal ankles) and 2.88±1.27 mm (previously injured ankles) and in women 1.92 ± 0.38 mm (normal ankles) and 2.06 ± 0.56 mm (previously injured ankles).

Table 2.3 Dimensions of the calcaneofibular ligament: NK; not known, DF; dorsiflexion, PF; plantarflexion.

Study	N	Study Mode/ Specimens	CFL Length (mm)	CFL Width (mm)	CFL Thickness (mm)
Testut and Latarjet, 1948; as cited by Milner and Soames, 1998a	NK	NK/ NK	30 – 40	4 - 5	
Ruth, 1961	75	30 dissected specimens/ 45 surgical operation		4 - 6	
Siegler et al., 1988	20	Dissection/ frozen	27.69 ± 3.3		
Buzzi et al., 1993	10	Dissection/ formalin embalmed	24.3	6.7	
Sarrafian, 1993a	NK	NK/ NK	30	5	3
Burks and Morgan, 1994	39	Dissection/ 30 frozen, 9 embalmed	35.8	5.3	
Luo et al., 1997	11	Dissection/ NK	20.6 ± 2.9		
Ahmad et al., 1998	19	MRI/ living individuals			3
Milner and Soames, 1998a	40	Dissection/ NK	19.5 ± 3.9	5.5 ± 1.6	
Sindel et al., 1998	24	Dissection/ NK	26.8 ± 4.91	6 ± 0.8	
Ozeki et al., 2002	12	Dissection/ fresh frozen	29.9 ± 4.24		
Butler and Walsh, 2004	8	Dissection/ fresh frozen			1.5 ± 0.2
Taser et al., 2006	42	Dissection/ unknown embalming	31.94 ± 3.68	Proximal: 7.19 ± 2.23 Middle: 4.68 ± 1.34 Distal: 9.68 ± 1.73 mm	
Dimmick et al., 2008	28	MRI/ living individuals			2.13 ± 0.5 men: 2.28±0.53 women: 1.92 ± 0.38
Hua et al., 2008	30	MRI/ living individuals			1.52 ± 0.21
De Asla et al., 2009	4	MRI and dual-orthogonal fluroscopy/ living individuals	Neutral: 28 ± 2.9 DF: 29.9 ± 3 PF: 26.6 ± 2.2 Supination: 26.9 ± 3.6 Pronation: 31 ± 3.8		
Uğurlu et al., 2010	22	Dissection/ formalin embalmed	26.67	4.57	
Boonthathip et al., 2011	10	MRI/ frozen	31 ± 6	4.6 ± 1	
Kitsoulis et al., 2011	72	Dissection/	31.83	4.42	1.58

		unknown embalming	CFL elongation (inversion, DF) 2.88 (male: 2.63; female: 3.28)		
Study	**N**	**Study mode/ specimens**	**Length (mm)**	**Width (mm)**	**Thickness (mm)**
Raheem and O'Brien, 2011	20	Dissection/ unknown embalming	Neutral: 18.5 ± 6.3 Dorsiflexion: 15.5 ± 6.3 Plantarflexion: 17 ± 5.6	7.5 ± 3.5	
Neuschwander et al., 2013	8	Dissection/ frozen	24.8 ± 2.4		
Yıldız and Yalcın, 2013	45	Dissection/ formalin embalmed	Shortest length: 15.03 ± 2.93 Longest length: 20.02 ± 2.99	5.44 ± 2.34	
Apoorva et al., 2014	60	Dissection/ formalin embalmed	27 ± 3.89	5.5 ± 1.12	1.65 ± 0.43
Wenny et al., 2014	17	Dissection/ formalin embalmed	cranial/posterior length: 20.88 ± 2.72 caudal/ anterior length: 21.59 ± 2.7	talar/calcaneal width: 7.66 ± 1.68 fibular/tibial width: 6.63 ± 1.61	
Haytmanek et al., 2015	11	Radiography (miniature fluoroscopy)/ fresh frozen	lateral view: 28.1 ± 4.8 mortise view: 24.5 ± 4.5		

2.5 Anatomy of the Posterior Talofibular Ligament (PTFL)

The posterior talofibular ligament (PTFL) (Figure 2.28) extends between the malleolar fossa of the lateral malleolus of the fibula and the posterior surface of the talus. It is intracapsular but extrasynovial and runs in a horizontal posteromedial direction forming the floor of the tunnel for flexor hallucis longus tendon (Taser et al., 2006): Luo et al. (1997) state that the PTFL passes posteroinferomedially in the neutral position. A posterior ligamentous sling formed by the upper segment of the PTFL has an attachment to the superficial tibiotalar ligament (STTL) (Taser et al., 2006). The PTFL consists of multifasciculated fibres or bands with the thickest two parts being an anterior short band and long posterior band (Boonthathip et al., 2011). It becomes taut in dorsiflexion and is relaxed in neutral and plantarflexion (Golanó et al., 2010). The PTFL has two groups of fibres: a long posterior group running inferomedially attaching to the talar posteromedial tubercle and short anterior group running medially attaching to the talar posterior border (Courvoisier et al., 2008). A posterior intermalleolar ligament fuses with some fibres of the PTFL (Paturet, 1951; as cited by Golano 2010).

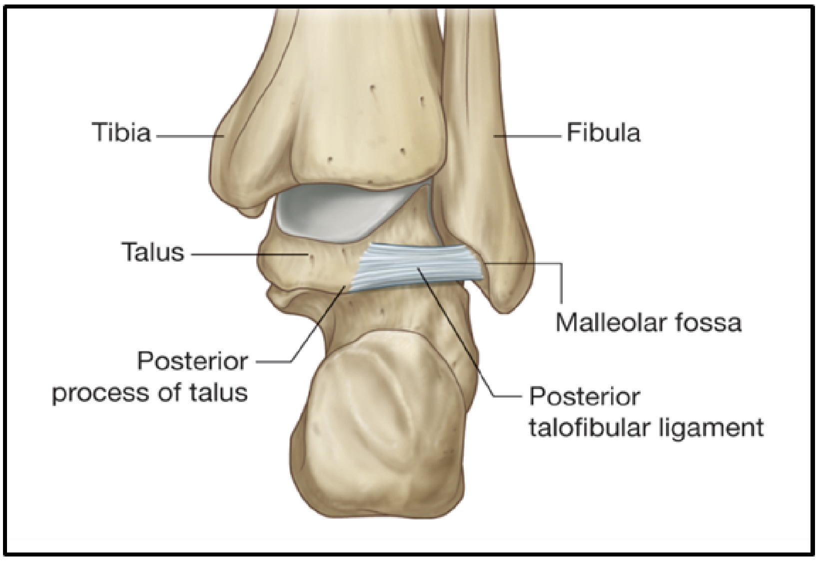

Figure 2.28 The posterior talofibular ligament (Drake et al., 2010b).

2.5.1 Proximal Attachment of the Posterior Talofibular Ligament (PTFL)

The proximal attachment of the posterior talofibular ligament (PTFL) originates from the medial surface of the lateral malleolus (Gursoy et al., 2015; Boonthathip et al., 2011; Sindel et al., 1998), from the inferior part of the malleolar fossa (Clanton et al., 2014; Taser et al., 2006) and from the posteroinferior part of the medial side of the malleolar fossa (Boonthathip et al., 2011).

The distance between the PTFL midproximal attachment and lateral malleolar tip was 4.8 mm (Clanton et al., 2014) (Figure 2.29), 10.45 ± 3.08 mm (Wenny et al., 2014), 8.2 ± 1.43 mm (Sindel et al., 1998) and 9.7 mm (Burks and Morgan, 1994). Moreover, the PTFL fibular footprint area was 94 mm² (Clanton et al., 2014) and 0.48 ± 0.06 cm² (Wenny et al., 2014). The proximal/distal dimension of the proximal PTFL attachment has been reported as 6.9 ± 0.69 mm, while the anteroposterior dimension of the proximal insertion was 8.2 ± 0.46 mm (Sindel et al., 1998) and 10.1 mm (Burks and Morgan, 1994).

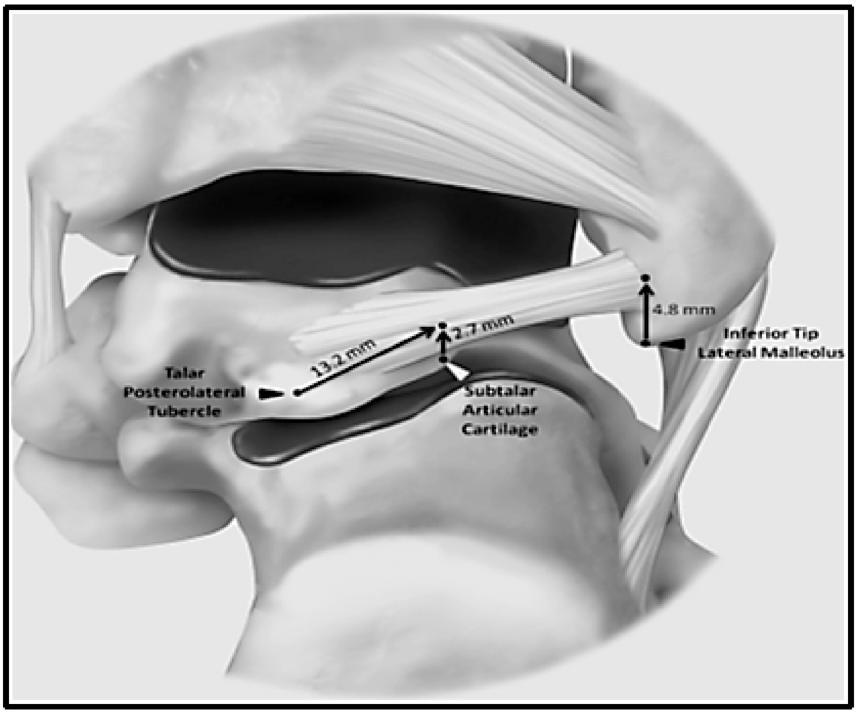

Figure 2.29 The distance between the PTFL proximal attachment and the tip of the lateral malleolus reported to be 4.8 mm (modified from Clanton et al., 2014).

2.5.2 Distal attachment of the Posterior Talofibular Ligament (PTFL)

The PTFL inserts distally to the posterior surface of the talus (Wenny et al., 2014; Hua et al., 2008; Burks and Morgan, 1994) and the lateral talar surface (Taser et al., 2006). The insertion has been described as lateral to the posterolateral tubercle of the talus, being between the talar trochlea and the lateral malleolar surface (Wenny et al., 2014). When an os trigonum is present the PTFL has an attachment to it (Gursoy et al., 2015; Golanó et al., 2010; Sarrafian, 1993a). However, Gursoy et al. (2015) observed the distal attachment of the anterior part of the PTFL was into the talar lateral surface, while the posterior part was to the posterolateral tubercle. The PTFL inserted distally 13.2 mm from the posterolateral tubercle and had a talar attachment area of 154.7 mm^2 (Clanton et al., 2014) and 65 ± 11 mm^2 (Wenny et al., 2014). Additionally, Sindel et al. (1998) reported the PTFL long attachment on the talus (distal bony attachment) as 20.7 ± 2.15 mm.

2.5.3 Posterior talofibular (PTFL) Dimensions

PTFL length has been reported to range between 10.5 mm and 41 mm (Table 2.4). However, Milner and Soames (1998a) state that measuring the true length of the PTFL was not possible as it has an almost complete bony attachment along the talus. Ruth (1961) reported the length of the part of the PTFL attached to the talus as 9 mm, while Sindel et al. (1998) found it to be 20.7 ± 2.15 mm.

Table 2.4 Dimensions of the posterior talofibular ligament (PTFL): NK, not known.

Study	N	Study Mode/ Specimens	PTFL Length (mm)	PTFL Width (mm)	PTFL Thickness (mm)
Ruth, 1961	75	30 dissected specimens/ 45 surgical operation		6	
Siegler et al., 1988	20	Dissection/ frozen	21.16 ± 3.86		
Sarrafian, 1993a	NK	NK/ NK	30	Proximal: 5	5 – 8
Buzzi et al., 1993	10	Dissection/ frozen	Short fibres: 17.4 Long fibres: 21.9	Proximal: 10.5	
Burks and Morgan, 1994	39	Dissection/ 30 frozen, 9 embalmed	24.1		
Luo et al., 1997	11	Dissection/ NK	14.2 ± 2.8		
Milner and Soames, 1998a	40	Dissection/ NK	23 ± 7	5.5 ± 2.5	
Sindel et al., 1998	24	Dissection/ NK	41 ± 2.81	6.1 ± 0.77	
Ozeki et al., 2002	12	Dissection/ fresh frozen	23.7 ± 3.1		
Butler and Walsh, 2004	8	Dissection/ fresh frozen			2.3 ± 0.6
Taser et al., 2006	42	Dissection/ unknown embalming	21.66 ± 4.84	5.55 ± 1.25 (middle)	
Uğurlu et al., 2010	22	Dissection/ formalin embalmed	24.12	5.09	
Boonthathip et al., 2011	10	MRI/ frozen	27.8 ± 3.6	8.7 ± 3	
Wenny et al., 2014	17	Dissection/ formalin embalmed	cranial/posterior length: 16.41 ± 2.58 caudal/anterior length: 17.38 ± 2.34	talar/calcaneal width: 5.09 ± 1.31 fibular/tibial Width: 4.74 ± 1.15	
Haytmanek et al., 2015	11	Radiography (miniature fluoroscopy)/ fresh frozen	lateral view: 10.5 ± 2 mortise view: 19.5 ± 2.5		

The width of the PTFL ranges between 4.74 and 8.7 mm, although previous studies did report difficulties in measurement. For example, difficulty of measuring PTFL width at 3 points has been reported due to its attachment to the talus (Taser et al., 2006). Furthermore, Burks and Morgan (1994) reported difficulty in measuring the width as it changed with ankle position. PTFL thickness, however, has only been reported twice, being 5 – 8 mm (Sarrafian, 1993a) and 2.3 ± 0.6 mm (Butler and Walsh, 2004).

2.6 Anatomy of the Ankle Medial Collateral Ligaments (MCL; Deltoid)

The deltoid ligament (medial collateral ligament; MCL) of the ankle (Figure 2.30) is a strong triangular ligament (Snell, 2008; Mackinnon and Morris, 2005; Norkus and Floyd, 2001) which originates from the tibial medial malleolus (Drake et al., 2010a) extending between its anterior and posterior borders (Standring, 2008) attaching to the tip of the medial malleolus (Snell, 2008) (Figure 2.31). It has a wide distal insertion extending between the talar medial tubercle and navicular as well as the calcaneus (Drake et al., 2010a; Klein, 1994). The flexor retinaculum and deep crural fascia invest most of the ligament apart from its anterior part. The anterior joint capsule is continuous with the anterior border of deltoid, while the posterior capsule is continuous with the posterior segment: the latter then continues with the posterior talofibular ligament (Sarrafian, 1993a).

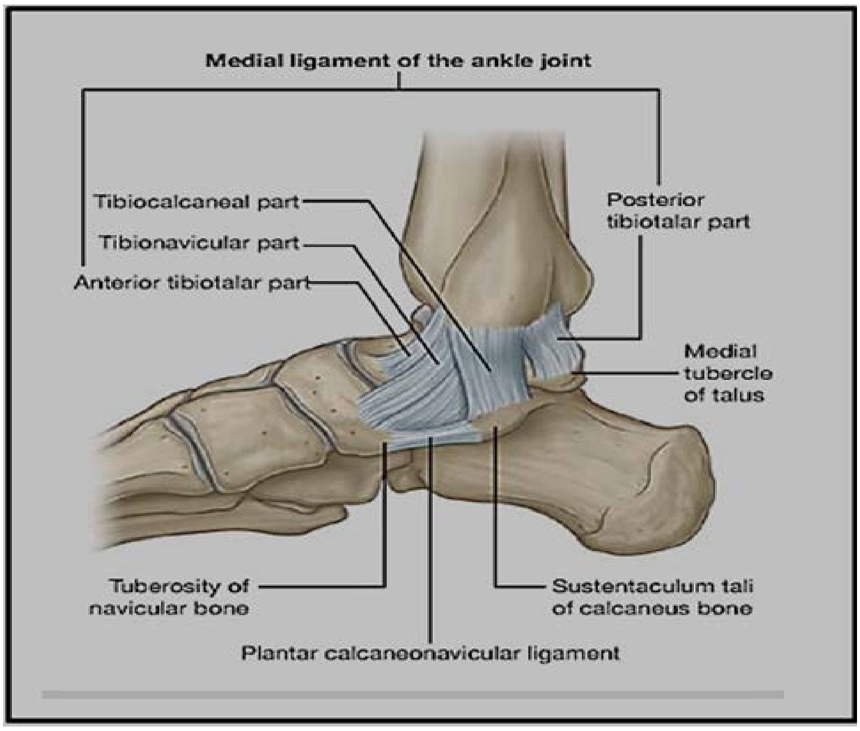

Figure 2.30 Deltoid ligament of the ankle joint (modified from Drake et al., 2010b).

The main function of deltoid ligament is to restrict talar abduction and support the medial aspect of the ankle anteriorly and posteriorly (Savage-Elliott et al., 2013): eversion is also stabilised by preventing ankle dislocation (Moore et al., 2010). Norkus and Floyd (2001) indicated that deltoid restricts excessive dorsiflexion, while minimising external talar rotation, especially the anterior part of the ligament. It is therefore not surprising that ankle instability and pain may result from injury to deltoid (Yu et al., 2015). Moreover, the ligament has been ignored in patients during the diagnosis or treatment of chronic lateral ankle instability. MRI has shown that 72% of patients with chronic ankle stability had an injury to deltoid although there was no medial ankle pain (Crim et al., 2011).

Diagnosing and treating ankle injuries require a sound knowledge of ankle ligament anatomy (Golanó et al., 2010). Reconstructing an injured deltoid requires knowledge of its morphology in order to recover the normal anatomy (Cromeens et al., 2015) and restrict external rotation and abduction of the talus (Sepúlveda et al., 2012). However, discrepancies in the literature on deltoid morphology may result in misdiagnosing an injury to this important complex (Savage-Elliott et al., 2013).

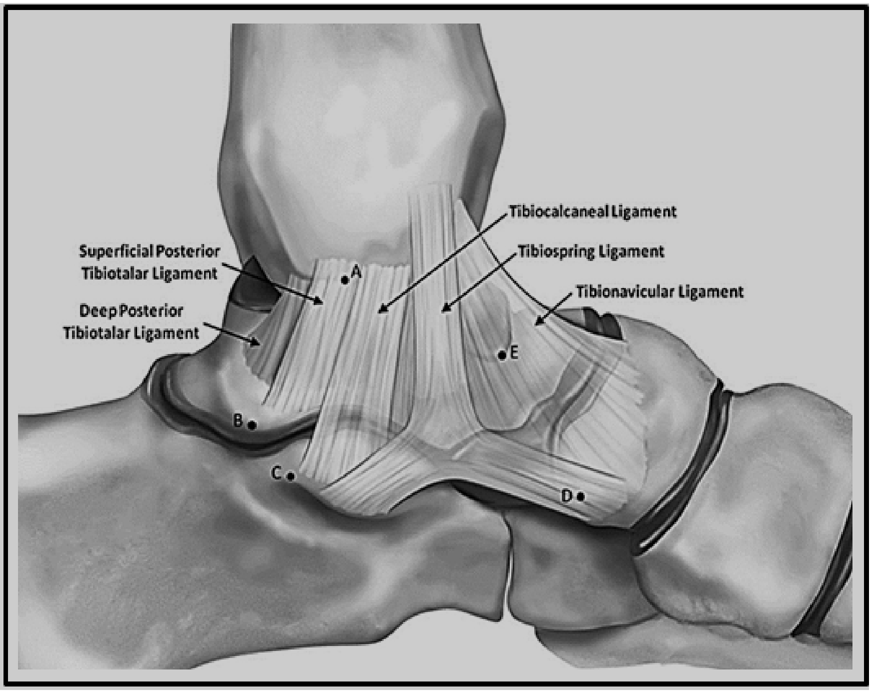

Figure 2.31 : Medial collateral ligaments of the ankle (modified from Campbell et al., 2014).

2.6.1 Components of the Ankle Medial Collateral Ligaments

The literature shows discrepancies in the components of the MCL, although they mainly agree that it consists of two layers: deep and superficial. Variations in deltoid anatomy have been observed, as well as differences in the naming of its various parts (Boss and Hintermann, 2002). A number of studies state that the MCL consists of 6 bands: tibionavicular (TNL), tibiocalcaneal (TCL), tibiospring (TSL), superficial tibiotalar (STTL) deep posterior tibiotalar (PTTL) and deep anterior tibiotalar (ATTL) ligaments (Campbell et al., 2014; Boss and Hintermann, 2002; Milner and Soames, 1998a; Milner and Soames, 1998b). However, this disagrees with many anatomy textbooks (Figure 2.30) in which the MCL is reported to consist of only 4 parts: TNL, TCL, PTTL and ATTL (Drake et al., 2010a; Moore et al., 2010; Standring, 2008; Palastanga et al., 2006; Norkus and Floyd, 2001; McMinn et al., 1996). Cromeens et al. (2015) reported that deltoid consists of the tibiocalcaneonavicular ligament (comprising the TNL, TSL and TCL), STTL, PTTL, ATTL and inferoplantar longitudinal ligament. Additionally, 8 bands were reported by Panchani et al. (2014), these being the ATTL, TNL, TCL, PTTL, STTL, fibres to the spring ligament, a band deep to the TCL (dTCL) and a band posterior to the sustentaculum tali (PST). Pankovich and Shivaram (1979a) observed only the TNL, TCL, STTL, ATTL and PTTL, while Hintermann and Golano (2014) considered the plantar calcaneonavicular (spring ligament) to be part of the deltoid complex. Milner and Soames (1998b) indicated that there was no relationship between the existence of additional bands and sex or age. As shown in Figures 2.32, 2.33 and 2.34 a number of descriptions of the MCL components have been put forward between 1822 and 1961.

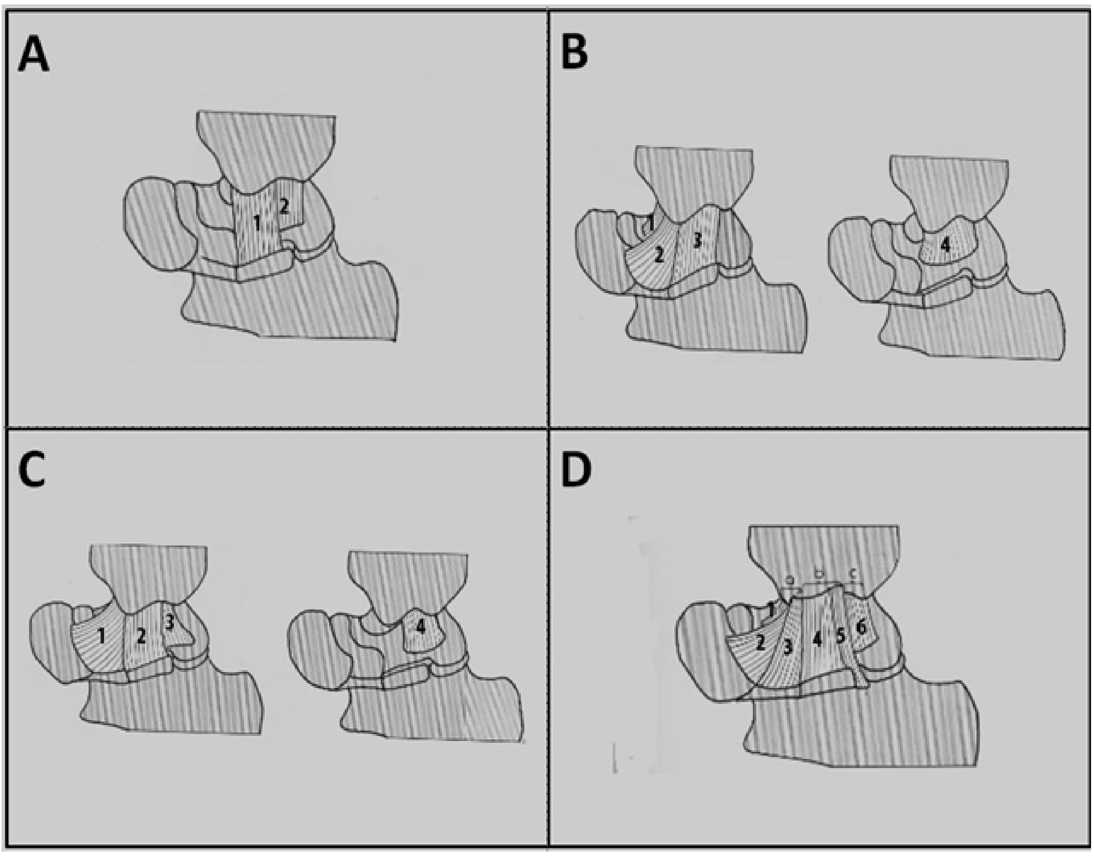

Figure 2.32 A, Cloquet (1822): attached proximally to the medial malleolar tip and depression and distally to 1. The calcaneus and 2. The talus; B, Cruveilhier (1834): originating from the medial malleolar tip and its borders and inserting to 1. the talar neck, 2. navicular, 3. calcaneus and 4. talar medial surface; C, Sappey (1888): 1. to the navicular, 2. the calcaneal sustentaculum tali, 3. talar posteromedial tubercle, and 4. the posterior part of the medial surface of the talus; D, Poirier and Charpy (1899): 1. to the talar neck, 2. navicular superior surface, 3. inferior spring ligament, 4. calcaneal sustentaculum tali, 5. calcaneal surface posterior to sustentaculum tali, and 6. talar medial surface inferior to tibial facet (modified from Sarrafian, 1993a).

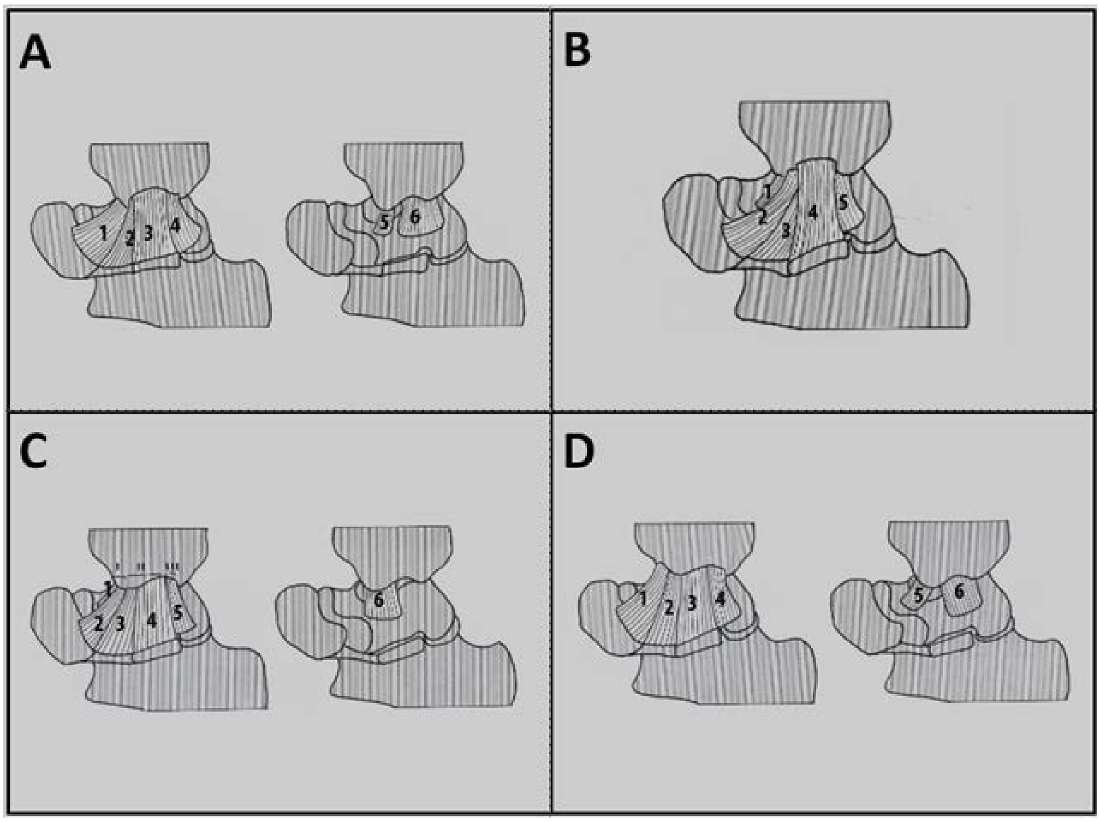

Figure 2.33 A, Toldt (1900): 1. the navicular and spring ligament (dorsal), 2. inferior spring, 3. sustentaculum tali, 4. talar posteromedial tubercle, 5. talar neck, and 6. the mid and posterior parts of the talar medial surface; B, Spalteholz (1903) - Fick (1904): 1. inferior to talar articular surface, 2. navicular dorsomedial surface, 3. medial edge of the spring ligament, 4. sustentaculum tali, and 5. mid and posterior parts of the talar medial surface as well as the talar posteromedial tubercle; C, Testut (1921): 1. the neck of the talus, 2. superior part of navicular, 3. inferior spring, 4. sustentaculum tali, and 5. the talar posteromedial tubercle (Sarrafian, 1993a); D, Dujarier (1924): 1. navicular, 2. inferior spring, 3. sustentaculum tali, 4. talar posteromedial tubercle. 5. neck of the talus, and 6. inferoposterior to the talar articular surface (modified from Sarrafian, 1993a).

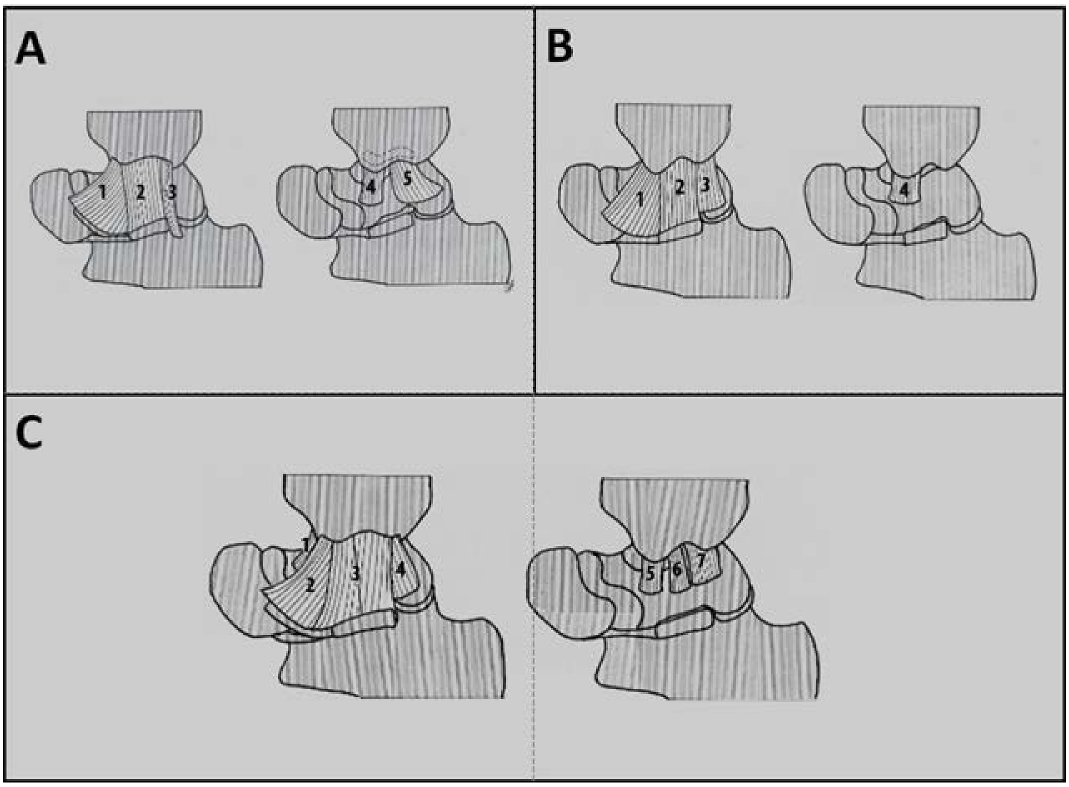

Figure 2.34 A, Paturet (1951): 1. navicular superomedial surface, talar neck medial aspect and superior talonavicular ligament, 2. inferior spring ligament and sustentaculum tali, 3. calcaneal medial surface posterior to sustentaculum tali reaching as far as the superior segment of the calcaneal canal. 4. talar medial surface inferior to the articular surface, and 5. the talar posteromedial tubercle reaching as far as the flexor hallucis longus tunnel; B, Gray (1954 – 1973): 1. navicular and spring ligament, 2. sustentaculum tali, 3. talar medial surface and posteromedial tubercle, and 4. talar medial surface; C, Yashar (1961): 1. talar neck inner aspect, 2. medial spring and superior surface of navicular. 3. medial spring ligament and sustentaculum tali as well as on its posterior part, and 4. the talar medial surface and posteromedial tubercle (modified from Sarrafian, 1993a).

2.6.2 Superficial Component of the MCL

The superficial bands of the MCL cross the tibiotalar (ankle) and subtalar joints (Boss and Hintermann, 2002), being separated from the deep layer by adipose tissue (Campbell et al., 2014), the superficial layer expanding around the joint capsule. The MCL is a continuous ligament with a wider distal attachment and no clear fasciculation (Sepúlveda et al., 2012).

2.6.3 Proximal and Distal Attachments of the Superficial MCL

The superficial layer originates proximally from the anterior border and medial part of the anterior colliculus and the posterior colliculus of the medial malleolus (Pankovich and Shivaram, 1979a), as well as from the inferior border of the medial malleolus (Sepúlveda et al., 2012). This layer's centre of attachment on the tibia was 9.45 ± 3.21 mm from the medial malleolar tip and 6.32 ± 2.45 mm from the anterior edge of the medial malleolus (Wenny et al., 2014). Its proximal tibial attachment area was 113 ± 15 mm^2 (Wenny et al., 2014).

The superficial layer inserts distally into the talar posteromedial tubercle, the sustentaculum tali and navicular (Pankovich and Shivaram, 1979a). However, Sepúlveda et al. (2012) found that the anterior and posterior tibiotalar fibres inserted into the talus, the tibionavicular fibres to the navicular, the tibiospring part to the spring ligament and the medial tibiocalcaneal part to the calcaneus. Wenny et al. (2014) reported that the distal insertion was divided to a calcaneal part that inserted into the sustentaculum tali and a navicular part that attached to the lateral dorsal part of the navicular close to the facet for the head of the talus. The superficial layer had a distal navicular attachment area of 119 ± 12 mm^2 and a distal calcaneal attachment area of 113 ± 24 mm^2 (Wenny et al., 2014).

2.6.4 Shape of the Superficial MCL

The shape of the superficial layer (Figure 2.35) is trapezoidal (fan shaped) in 70.4%, rectangular in 18.5% and triangular in 11.1% (Sepúlveda et al. 2012). In addition, 74.1% of specimens had the superficial layer completely covering the deep layer, while there was incomplete covering in 25%. The incomplete covering was observed in 60% of rectangular shaped ligaments and 21% with a trapezoid shape: all triangular shapes had the superficial layer completely covering the deep layer. The shape of the superficial layer may affect the vulnerability of the deep layer to rupture, which can occur when it is incompletely covered. For example, a rectangular shaped superficial layer may result in the deep layer having to resist greater tension that could result in rupture of the deep layer.

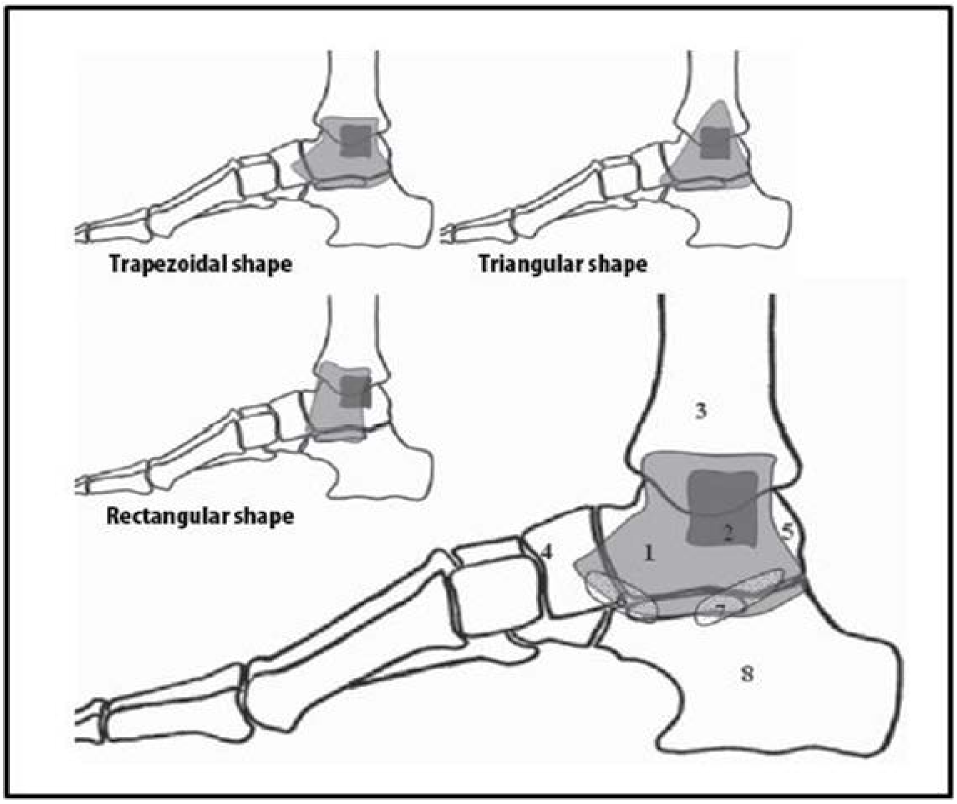

Figure 2.35 Superficial MCL shapes; 1, superficial layer; 2, deep deltoid; 3, tibia; 4, navicular; 5, talus; 6, plantar calcaneonavicular ligament; 7, medial talocalcaneal ligament; 8, calcaneus (modified from Sepúlveda et al., 2012).

2.6.5 Dimensions of the Superficial MCL

Measurement of the superficial deltoid ligament (Figure 2.35) was undertaken in relation to ligament shape by Sepúlveda et al. (2012). The trapezoidal shape had an anterior side length of 30.6 ± 10.3 mm, posterior side of 28.5 ± 8.5 mm, superior side of 22.5 ± 3.7 mm and inferior side length of 48.4 ± 8.9 mm. The rectangular shape had a length of 21 ± 7.2 mm, 24.8 ± 7.3 mm, 22.7 ± 6.9 mm and 28.2 ± 7.6 mm for the anterior, posterior, superior and the inferior sides respectively. The triangular shape measured 37 ± 10.6 mm (anterior side), 37.8 ± 3.9 mm (posterior side) and 48.3 ± 6.4 mm (inferior side). Wenny et al. (2014) reported the cranial/posterior length was 18.97 ± 4.4 mm, caudal/anterior length 21.59 ± 4.1 mm and the talar/calcaneal width as 15.97 ± 2.8 mm. The fibular/tibial width was 9.69 ± 2.26 mm (Wenny et al., 2014) and thickness 5.2 ± 1.5 mm (Sepúlveda et al., 2012).

2.6.6 Superficial MCL Ligaments

Variations in the different parts of the superficial layer have been reported, comprising mainly the TNL, TCL, TSL and STTL (Campbell et al., 2014; Boss and Hintermann, 2002; Milner and Soames, 1998a; Milner and Soames, 1998b). However, Siegler et al. (1988) included the TNL, TSL and TCL but not the STTL, while Pankovich and Shivaram (1979a) included the TNL, TCL and STTL but not the TSL. The superficial MCL has also been reported to consist of only two parts: TNL and TCL (Drake et al., 2010a; Moore et al., 2010; Palastanga et al., 2006; Norkus and Floyd, 2001). However, Cromeens et al. (2015) state that the tibiocalcaneonavicular and STTL form the superficial layer. Panchani et al. (2014) observed that the superficial deltoid consisted of the

TNL, TCL, STTL, fibres to the spring ligament and a superficial band that was posterior to the sustentaculum tali (PST). However, Standring (2008) reported the posterior tibiotalar ligament to be part of the superficial fibres of deltoid. Sarrafian (1993a) reported a superficial tibiotalar fascicle sharing a common origin with the TNL.

2.6.7 Tibionavicular Ligament (TNL)

The TNL is reported to be a consistent band in a number of studies (Campbell et al., 2014; Milner and Soames, 1998b), being a fan shaped triangular band and considered to be the weakest of the bands, even though it is the longest and the widest band. It fuses with the capsule from the anterolateral side, as well as being continuous with the TCL (Pankovich and Shivaram, 1979a). It passes anteriorly and downward and then backward when attaching to the spring ligament (Palastanga et al., 2006), and is directed anteriorly to the longitudinal tibial axis (Boss and Hintermann, 2002). It has been reported to have an inferior, anterior and lateral orientation (Luo et al., 1997). However, Boss and Hintermann (2002) suggest that the TNL should not be considered a ligament; rather it is a fibrous layer of the joint capsule.

Panchani et al. (2014) found that separating the joint capsule from the TNL was difficult and could only be successfully isolated in 29 of 33 specimens. The proximal attachment of the TNL was to the medial malleolus (Panchani et al., 2014) inserting to the anterior border of the anterior colliculus (Milner and Soames, 1998b). It originated 16.1 mm from the distal centre of the intercollicular groove of the medial malleolus, with a tibial footprint area of 54 mm^2 (Figure 2.36) (Campbell et al., 2014).

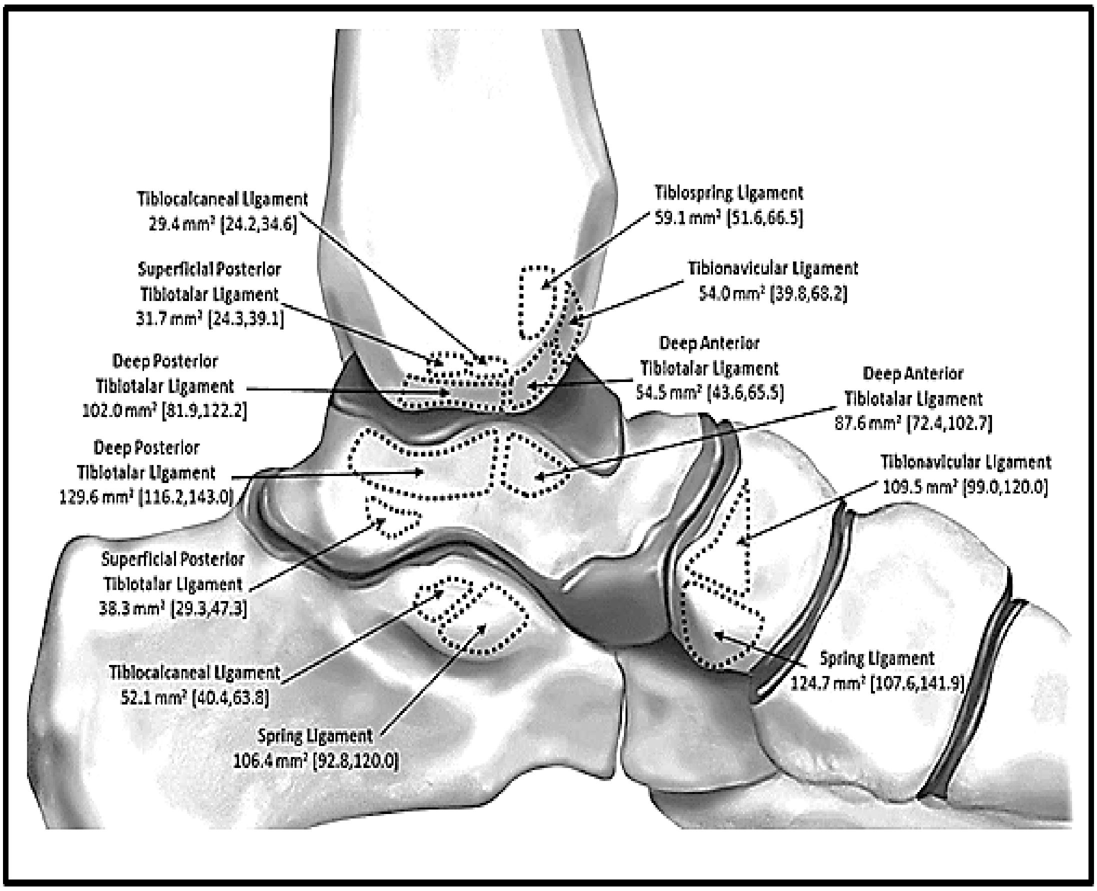

Figure 2.36 Proximal and distal attachment areas of the various deltoid bands (modified from Campbell et al., 2014).

The distal attachment of the TNL was to the dorsomedial aspect of the navicular (Panchani et al., 2014; Palastanga et al., 2006; Pankovich and Shivaram, 1979a) and the superomedial part of the spring ligament (Palastanga et al., 2006). Moreover, part of the TNL may have an attachment to the talus, however this part was not considered as an individual band (Milner and Soames, 1998b). The distance between the distal attachment of the TNL and the navicular tuberosity along the line of the talonavicular joint was 9.7 mm, while the distance between the distal TNL attachment and the talonavicular joint was 3.4 mm: it had a navicular footprint area of 109.5 mm^2 (Figure 2.36) (Campbell et al., 2014).

TNL length was measured as 41.83 ± 4.93 mm and 32.5 ± 4.7 mm by Siegler et al. (1988) and Luo et al. (1997) respectively. Milner and Soames (1998a) measured the TNL length used a different method due to its shape, with the length of the anterior and posterior borders being 28.5 ± 5.9 mm and 15.5 ± 4.4 mm respectively. Panchani et al. (2014) found the TNL was the longest of the MCL bands, but there was no significant difference in lengths. TNL width was 11 ± 3.8 mm (proximal), 13.5 ± 5.4 mm (middle) and 27.5 ± 10.3 mm (distal) (Milner and Soames, 1998a). The thickness varies (Klein, 1994), being 1.6 mm; 1.4 mm (females) and 1.9 mm (males) using MRI (Mengiardi et al., 2007).The cross section area of the ligament was 7.1 ± 2.6 mm^2 (Siegler et al., 1988).

2.6.8 Tibiospring Ligament (TSL)

The tibiospring ligament (Figure 2.31) is curved anteriorly and it has been referred to as the tibioligamentous fascicle (Sarrafian, 1993a). It was described as a thin band (Campbell et al., 2014) and considered the most superficial part that always overlapped the TCL (Milner and Soames, 1998b). Both Boss and Hintermann (2002) and Milner and Soames (1998b) reported the TSL to be a constant band; however, Panchani et al. (2014) found it difficult to separate the TSL from the TCL and TNL, and managed to do so in only 15 of 33 specimens. The TSL formed an angle of - 7° ± 9° with the long axis of the tibia (Boss and

Hintermann, 2002). The TSL proximal attachment was between the TCL and TNL (Panchani et al., 2014), being to the anterior part of the anterior colliculus (Sarrafian, 1993a) superior and posterior to the TNL (Campbell et al., 2014). The distance between the TSL tibial attachment and the distal centre of the intercollicular groove was 13.1 mm (Campbell et al., 2014). The proximal tibial attachment area was reported as 21.3 ± 10.1 mm² (Boss and Hintermann, 2002) and 59.1 mm² (Figure 2.36) (Campbell et al., 2014).

The distal TSL attachment was into the superior part of the spring ligament (plantar calacneonavicular ligament) (Panchani et al., 2014; Milner and Soames, 1998b; Klein, 1994; Sarrafian, 1993a). Campbell et al. (2014) indicated that the TSL attached distally to the spring ligament along 35% of its posteroanterior length. The TSL distal attachment area was 34.2 ± 17.7 mm² (Boss and Hintermann, 2002).

TSL length in previous studies has been reported as 18.59 ± 4.37 mm (Siegler et al., 1988), 18.5 ± 6.3 mm (Milner and Soames, 1998a), 25 mm (Campbell et al., 2014), 24.3 ± 4 mm (Boss and Hintermann, 2002). TSL width was 9 ± 3.9 mm (Milner and Soames, 1998a), while Campbell et al. (2014) reported the width at the spring junction was 5.9 mm. In cadaveric specimens TSL thickness was 1.5 ± 0.5 mm (Boss and Hintermann, 2002), while determined from MRI it was 2 mm (females: 1.8 mm; males: 2.2 mm) (Mengiardi et al., 2007). The TSL had a cross sectional area of 13.5 ± 7.1 mm² (Siegler et al., 1988).

2.6.9 Tibiocalcaneal Ligament (TCL)

The tibiocalcaneal ligament (TCL) (Figure 2.37) is considered the strongest of all the superficial parts of the deltoid ligament (Sarrafian, 1993a). However, there is disagreement concerning its existence. Boss and Hintermann (2002) observed the TCL to be a consistent band, while others observed it in 15% to 94% of specimens (Campbell et al., 2014; Panchani et al., 2014; Milner and Soames, 1998b). Furthermore, there are differences in naming the various parts of deltoid such as the TCL and TSL (Boss and Hintermann, 2002). TCL direction has been described as vertical (Palastanga et al., 2006; Sarrafian, 1993a) and perpendicular (Pankovich and Shivaram, 1979a), while Luo et al. (1997) demonstrated that the TCL had an inferior, lateral and posterior orientation. Boss and Hintermann (2002) confirmed that it was not possible to separate the TCL from the PTTL, although it could be separated from the STTL. They reported the angle between the TCL and the long axis of the tibia as 21°± 17°. According to Sarrafian (1993a) the TCL is continuous with the TSL, which overlaps its proximal attachment in some cases.

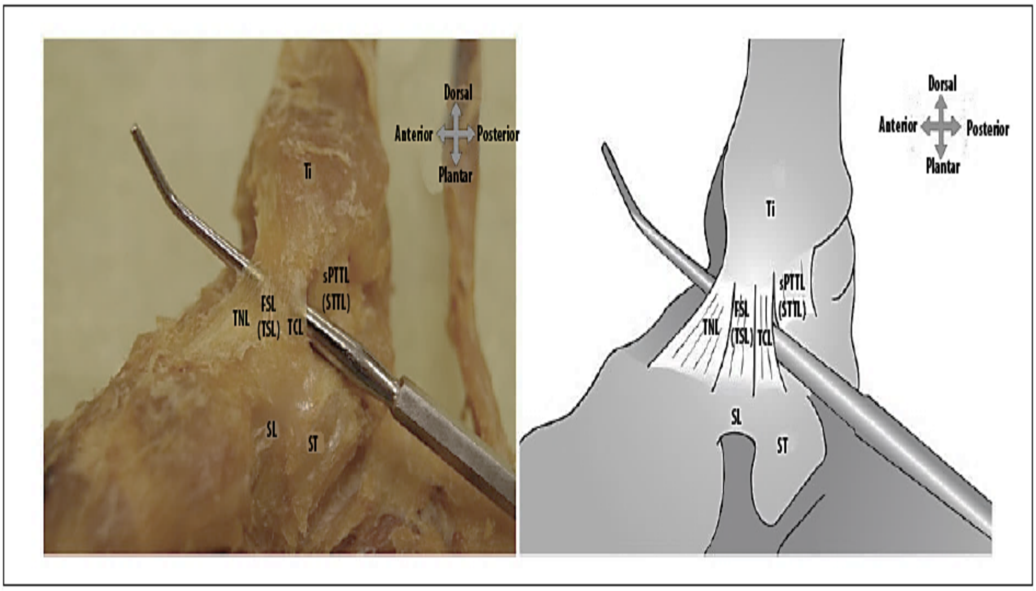

Figure 2.37 MCL superficial layer: TNL, tibionavicular ligament; FSL, fibres to spring ligament; SL, spring ligament; TCL, tibiocalcaneal ligament; sPTTL, superficial tibiotalar band; ST, sustentaculum tali; Ti, tibia (modified from Panchani et al., 2014).

The TCL is attached proximally to the medial surface of the medial malleolus (Panchani et al., 2014); to the medial surface of the anterior colliculus (Sarrafian, 1993a; Pankovich and Shivaram, 1979a) near the intercollicular groove (Campbell et al., 2014). The distance between the TCL tibial attachment and the distal centre of the intercollicular groove was 6 mm (Campbell et al., 2014) and had a tibial attachment area of 17.1 ± 9.4 mm^2 (Boss and Hintermann, 2002) and 29.4 mm^2 (Campbell et al., 2014).

The TCL is attached distally to the medial edge of the sustentaculum tali (Milner and Soames, 1998b; Sarrafian, 1993a; Pankovich and Shivaram, 1979a). However, reports of the distal attachment vary between the posterior part of the sustentaculum tali, posterior to the spring ligament (Campbell et al., 2014), to the superior part of the sustentaculum tali (Figure 2.37) (Panchani et al., 2014) and to the whole sustentaculum tali (Palastanga et al., 2006). In addition, Sarrafian (1993a) reported that some TCL fibres attach to the spring ligament. The distance between the TCL distal attachment and the posterior point of the sustentaculum tali was 8 mm (Campbell et al., 2014), and had a footprint area of 19.8 ± 10.9 mm^2 (Boss and Hintermann, 2002) and 52.1 mm^2 (Campbell et al., 2014).

TCL length has been reported to differ (Panchani et al., 2014), being 25.6 ± 4.5 mm (Boss and Hintermann, 2002), 27.7 ± 3.76 mm (Ozeki et al., 2002), 18 ± 7.7 mm (Milner and Soames, 1998a), 28.8 mm (Campbell et al., 2014), 22.1 ± 3.5 mm (Luo et al., 1997) and 20 - 30 mm (Sarrafian, 1993a). Its width was reported as 9.5 ± 3.9 mm (proximal), 12 ± 5.8 mm (middle) and 22 ± 14.3 mm (distal) (Milner and Soames, 1998a), while Sarrafian (1993a) stated the width at origin and insertion as 10 mm and 15 mm respectively. TCL thickness was 2 – 3 mm (Sarrafian, 1993a), 1.8 ± 1.5 mm (Boss and Hintermann, 2002) and 2.8 ± 0.6 mm (Butler and Walsh, 2004); MRI thickness was variable (Klein, 1994) being 1.2 mm (women: 1.1 mm; men: 1.3 mm) (Mengiardi et al., 2007).

2.6.10 Superficial Posterior Tibiotalar Ligament (STTL)

The superficial posterior tibiotalar ligament (Figure 2.31) is one of the superficial bands about which there has been disagreement (Moore et al., 2010; Palastanga et al., 2006; Siegler et al., 1988). Nevertheless, the STLL has been reported in a number of studies to be present in 97% (Panchani et al., 2014), 79% (Campbell et al., 2014), 75% (Boss and Hintermann, 2002), 37.5% (Milner and Soames, 1998b), with Milner and Soames (1998b) observing it to be bilateral in 4 of 11 specimens. Panchani et al. (2014) observed the STTL to be present bilaterally in 93.75%. The ligament is located posterior and lateral to the TNL passing in an inferoposterior direction (Cromeens et al., 2015) superficial to the ATTL and PTTL (Boss and Hintermann, 2002). It forms an angle of - 20° ± 14° with the long axis of the tibia (Boss and Hintermann, 2002). Although it blends with the TCL it can be differentiated by their distal insertions to the talus and sustentaculum tali. Nevertheless, in some cases the STTL is partially separated from the TCL (Pankovich and Shivaram, 1979a), agreeing with Boss and Hintermann (2002). The STTL is taut in the dorsiflexed ankle (Pankovich and Shivaram, 1979a).

There is disagreement about the proximal attachment of the STLL. Cromeens et al. (2015) reported the origin to be the medial surface of the anterior colliculus, Milner and Soames (1998b) stated it was to the medial side of the posterior colliculus, Panchani et al. (2014) to the posteromedial surface of the tibial medial malleolus, and Pankovich and Shivaram (1979a) to the medial surface of the posterior segment of the anterior colliculus and partly from the posterior colliculus. The STTL origin was close to the inferior centre of the intercollicular groove, being 3.5 mm from it (Campbell et al., 2014). The proximal attachment area was 13.8 ± 5.5 mm^2 (Boss and Hintermann, 2002) and 31.7 mm^2 (Figure 2.36) (Campbell et al., 2014). Cromeens et al. (2015) measured the STLL tibial attachment as 32.34 ± 17.68 mm^2; the STTL had 13.78% of the total tibial attachment of the deltoid ligament.

Different descriptions of the distal attachment of the STTL have been reported, nevertheless it always inserted to the talus with 66.66% also inserting to the posterosuperior part of the sustentaculum tali (Cromeens et al., 2015). Panchani et al. (2014) reported the insertion to be to the talar superoposterior surface, while Campbell et al. (2014) stated that its talar attachment was on the posteroinferior part of the medial surface of the talus 10.4 mm anterosuperior to the talar posteromedial tubercle.

Pankovich and Shivaram (1979a) indicated that the STTL insertion was into the anterior part of the talar posteromedial tubercle, while Milner and Soames (1998b) reported it to be to the sustentaculum tali and talar posteromedial tubercle. The distal insertion area reported by Boss and Hintermann (2002) was 16.7 ± 7.3 mm². Cromeens et al. (2015) measured the STLL talar and calcaneal attachment areas as 26.39 ± 17.42 mm² and 21.27 ± 2.25 mm² respectively, with Campbell et al. (2014) reporting the talar footprint area as 38.3 mm². The STTL had 14.7% and 10.41% of the total talar and calcaneal attachment of deltoid respectively (Cromeens et al., 2015).

STTL length reported in the literature show differences (Panchani et al., 2014), being 20 ± 4.3 mm (Boss and Hintermann, 2002), 21 mm (Campbell et al., 2014) and 14 ± 3.7 mm (Milner and Soames, 1998a). STTL width and thickness was 8 ± 2.8 mm (Milner and Soames, 1998a) and 1.2 ± 0.5 mm (Boss and Hintermann, 2002). MCL shape (Figure 2.38) led Cromeens et al. (2015) to present different measurements as is shown in Table 2.5.

Table 2.5 Dimensions of the STTL (Cromeens et al., 2015).

Measurement	Mean (mm)	Standard Deviation
2a: Tibiocalcaneal span	30.4	4.9
2b: Tibial attachment	11	4.7
2c: Tibiotalar span	28.5	3
2d: Talar attachment	5.9	2.7
2e: Calcaneal attachment	7.6	2.4
Thickness midspan of 2c	0.9	0.4

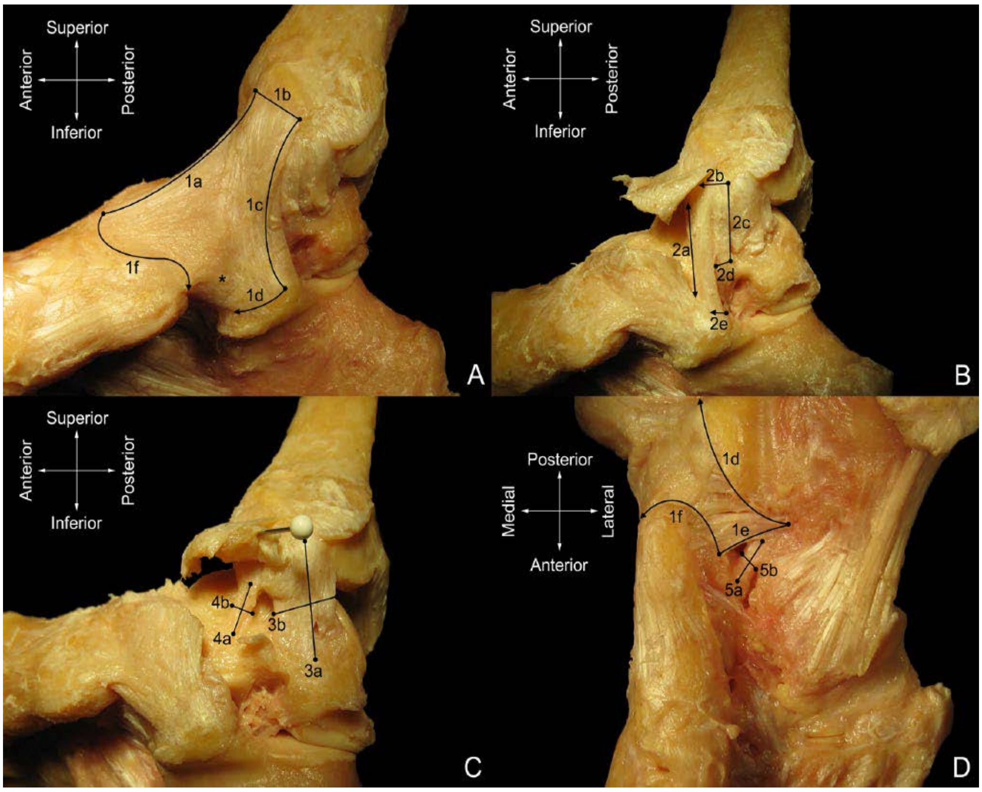

Figure 2.38 Measurements taken with respect to the MCL band shapes: A, measurements of the tibiocalcaneonavicular ligament; B, STTL measurements; C, ATTL and PTTL measurements; D, inferoplantar longitudinal measurements (Cromeens et al., 2015).

2.6.11 Tibiocalcaneonavicular Ligament

Cromeens et al. (2015) was the only study that reported the tibiocalcaneonavicular ligament (Figure 2.39) as being consistent, having an anterior direction. The tibiocalcaneonavicular ligament is the largest and most complicated part being composed of various named parts in other studies: TNL, TSL and TCL. It comprises 50 % of the whole attachment area of the deltoid ligament.

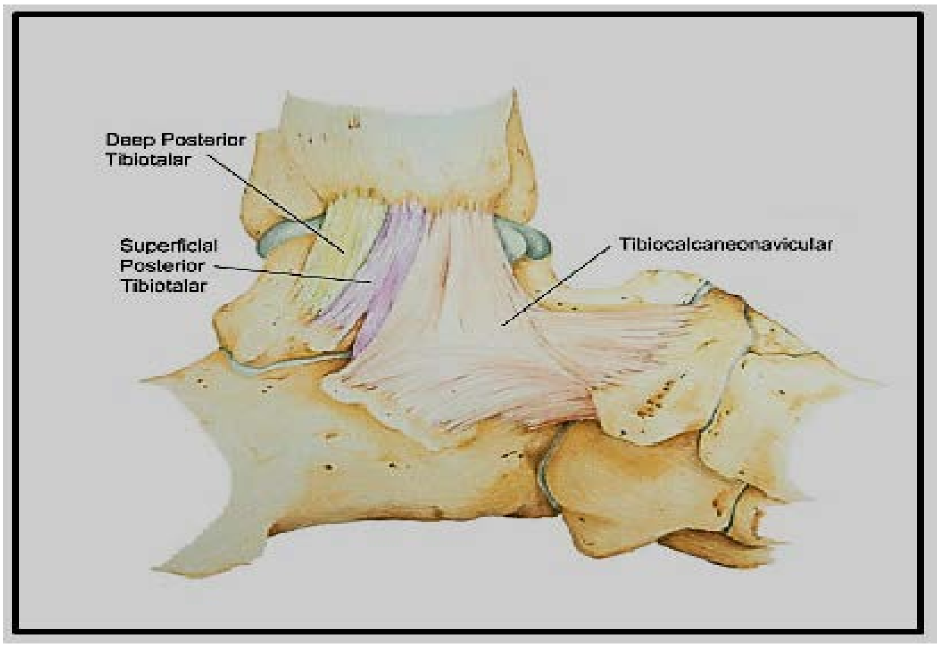

Figure 2.39 Tibiocalcaneonavicular ligament (modified from Cromeens et al., 2015).

The ligament originates proximally from the anterior border and medial part of the anterior colliculus of the medial malleolus, having a tibial attachment area of 93 ± 42.11 mm², comprising 10.46% of the total deltoid bony attachment area. In addition, it had 37.29% of the total tibial attachment of deltoid (Cromeens et al., 2015). It inserted distally to the calcaneus attaching to the posteromedial edge of the sustentaculum tali and coronoid fossa, the navicular between the lateral ¼ and medial ¾, then to the tuberosity of the navicular all the way to its plantar surface and then variable points of attachment between the navicular tuberosity and navicular beak. It had calcaneal and navicular attachment areas of 165.3 ± 33.11 mm² and 196.68 ± 54.4 mm² respectively, comprising 19.24% and 22.27% of the total bony attachment of deltoid respectively. In addition, it had 80.82% and 79.71% of the total calcaneal and navicular attachment of deltoid respectively (Cromeens et al., 2015).

A sling was formed by the distal attachments of the parts of the ligament surrounding the talar head. Therefore, the tibiocalcaneonavicular complex functions to support the head of the talus, thereby maintaining the medial longitudinal arch and the closeness of the navicular to the calcaneus. In addition, it has been suggested that the attachment sites of deltoid in relation to the superomedial spring ligament suggest that they function as a group (Cromeens et al., 2015). To determine the size of the tibiocalcaneonavicular ligament different measurements have been taken due to its shape (Figure 2.38): these are presented in Table 2.6.

Table 2.6 Tibiocalcaneonavicular ligament measurements (Cromeens et al., 2015).

Measurement	**Mean (mm)**	**Standard Deviation**
1a: Tibionavicular span	51.8	3.6
1b: Tibial attachment	14.7	3.3
1c: Tibiocalcaneal span	36.9	4.5
1d: Calcaneal attachment	35.2	2.7
1e: Calcaneonavicular span	23.2	3.9
1f: Navicular attachment	51.2	6.7
Thickness midspan of 1a	0.5	0.2
Thickness midspan of 1c	1.4	0.2
Thickness of the asterisk pointed	3.7	0.6

2.6.12 Band posterior to the sustentaculum tali (PST)

A band posterior to the sustentaculum tali (Figure 2.40) was observed by Panchani et al. (2014) and reported to be part of the superficial layer of deltoid: it was observed in 6% of cases. The PST had a proximal attachment the same as the TCL to the medial surface of the medial malleolus, being continuous with the TCL but separating after the TCL inserted to the sustentaculum tali. The ligament attached distally to the medial surface of the calcaneus posterior to the sustentaculum tali (Panchani et al., 2014).

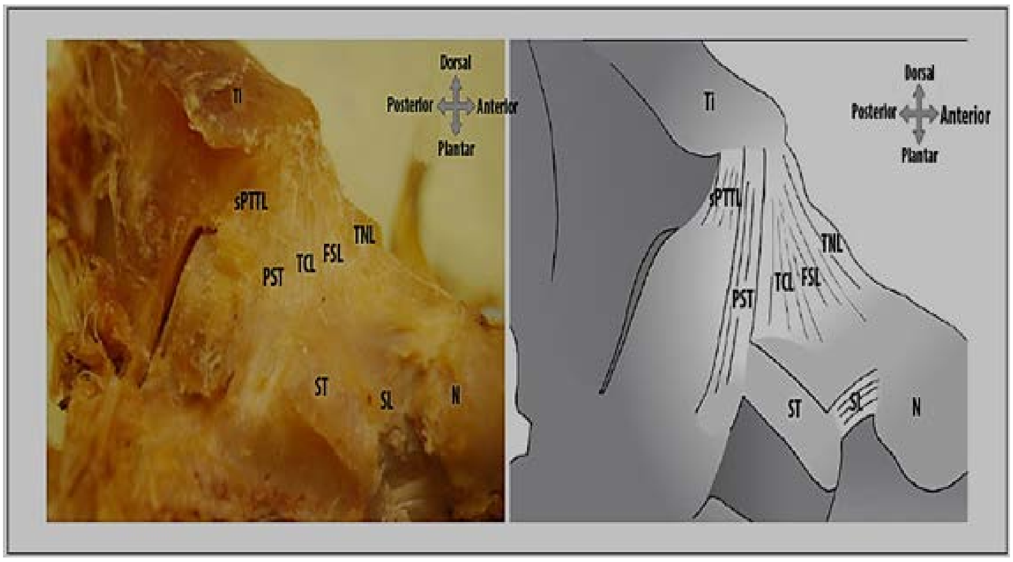

Figure 2.40 Band posterior to the sustentaculum tali (PST): FSL, fibres to the spring ligament; sPTTL, superficial tibiotalar ligament; TI, tibia; SL, spring ligament; ST, sustentaculum tali; N, navicular (modified from Panchani et al., 2014).

2.6.13 Deep Layer of the Deltoid Ligament

The deep layer of deltoid consists of the ATTL and PTTL (Figure 2.41) originating from the intercollicular groove of the medial malleolus, the posterior colliculus and partly from the anterior colliculus: it inserted distally to the talar medial surface (Pankovich and Shivaram, 1979a). Panchani et al. (2014) reported an additional deep band which they named the band deep to the TCL (dTCL). Sepúlveda et al. (2012) stated that the morphology of the deep layer was consistent and there were no variations, subdivisions or differentiation between the anterior and posterior parts; additionally they stated that the deep layer of deltoid is always rectangular in shape (Sepúlveda et al., 2012), with a length, width and thickness of 6.7 mm, 10.9 mm and 5.4 mm respectively.

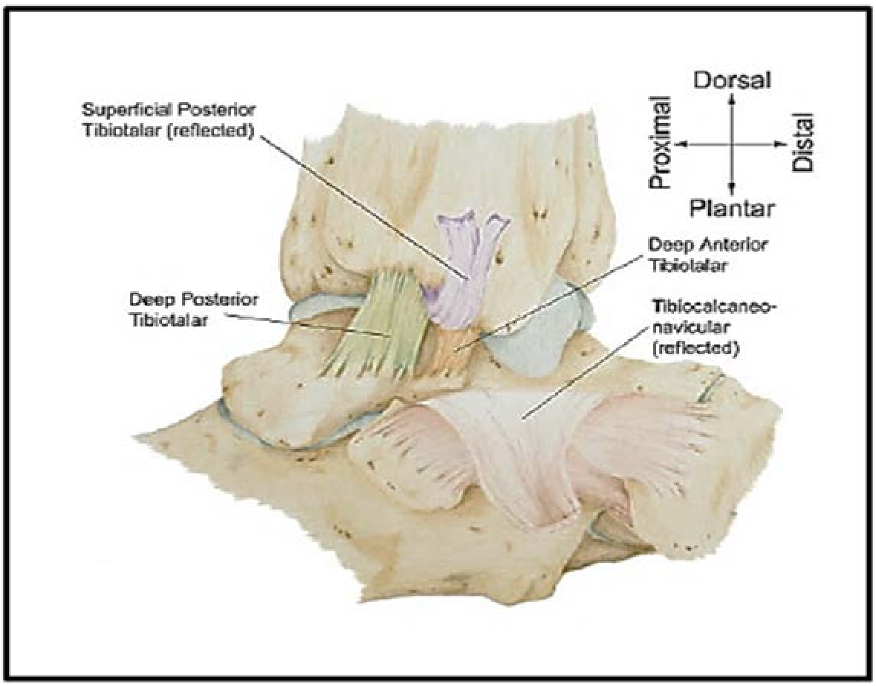

Figure 2.41 Deep component of the deltoid ligament (modified from Cromeens et al., 2015).

2.6.14 Deep Posterior Tibiotalar Ligament (PTTL)

The deep posterior tibiotalar ligament (PTTL) (Figure 2.41) is the main component of the deep layer of the deltoid ligament. Most previous studies report it as a consistent band of the deep MCL (Cromeens et al., 2015; Campbell et al., 2014; Panchani et al., 2014; Boss and Hintermann, 2002), describing it as a strong band (Pankovich and Shivaram, 1979a) being the thickest part of deltoid (Campbell et al., 2014). The ligament formed an angle of - 37° ± 11° with the long axis of the tibia (Boss and Hintermann, 2002), running inferiorly, laterally and posteriorly in the neutral position (Luo et al., 1997). The PTTL is covered by the STTL (Panchani et al., 2014) or the STTL and TCL (Campbell et al., 2014) and has been observed to run in a posterolateral direction (Standring, 2008; Palastanga et al., 2006; Pankovich and Shivaram, 1979a). Moreover, Milner and Soames (1998b) observed PTTL fasciculation, but there was no evidence of multiple bands. The PTTL is the main medial stabilizer of the talocrural joint as it has the greatest attachment area to the tibia and talus (Cromeens et al., 2015).

The PTTL is attached proximally to the intercollicular groove, anterior part of the posterior colliculus and posterior part of the anterior colliculus (Cromeens et al., 2015; Milner and Soames, 1998b). Pankovich and Shivaram (1979a) stated that some fibres reach the anterior colliculus (Figure 2.42). However, Klein (1994) observed the origin to be from the intercollicular groove and posterior colliculus. The centre of the proximal attachment was 7.6 mm from the distal centre of the intercollicular groove of the medial malleolus (Campbell et al., 2014). Wenny et al. (2014) reported the distance between the centre of the tibial attachment of the deep deltoid and the medial malleolar tip as 5.89 ± 2.89 mm, and to the anterior border of the medial malleolus 9.3 ± 3.04 mm. The PTTL proximal attachment area was 24.3 ± 21.9 mm² (Boss and Hintermann, 2002) and 111.65 ± 27.42 mm² comprising 12.82% of the total bony attachment of deltoid (Cromeens et al., 2015). The PTTL formed 46.42% of the total tibial attachment of deltoid (Cromeens et al., 2015). However, Wenny et al. (2014) reported the ATTL and PTTL total proximal blending attachment area as 101 ± 13 mm^2.

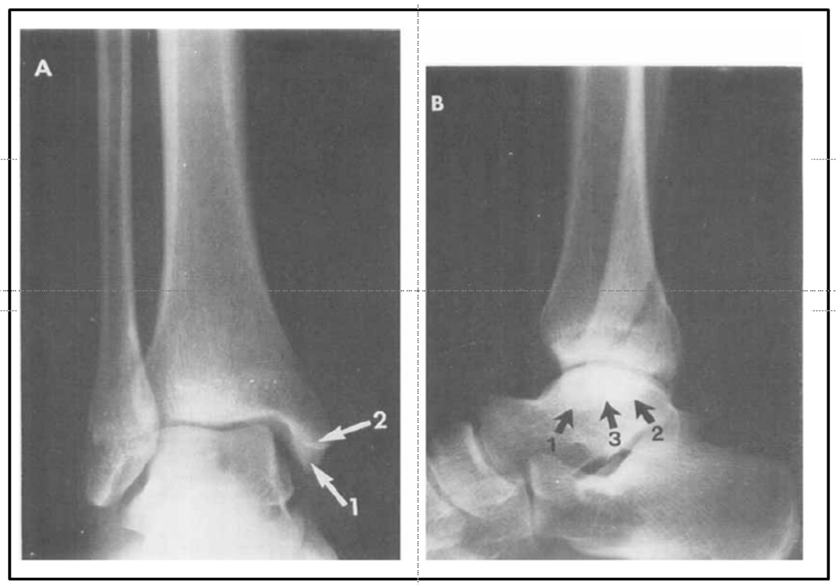

Figure 2.42 Radiographic image of the medial malleolus; A, anteroposterior view; B, lateral view; 1, anterior colliculus; 2, posterior colliculus; 3, intercollicular groove (Pankovich and Shivaram, 1979b).

The PTTL distal insertion (Figure 2.43) has been reported as the talar medial surface (Cromeens et al., 2015; Drake et al., 2010a; Palastanga et al., 2006) and attaching to the posteromedial tubercle of the talus (Drake et al., 2010a; Standring, 2008; Palastanga et al., 2006; Milner and Soames, 1998b; Pankovich and Shivaram, 1979a). However, Wenny et al. (2014) and Campbell et al. (2014) reported that it attached anterior and anterosuperior to the posteromedial tubercle and superior to the posterior subtalar facet respectively. In addition, the insertion is stated as being inferior to the facies malleolaris medialis (medial malleolar articular surface) (Figure 2.43) (Cromeens et al., 2015). Boss and Hintermann (2002) and Wenny et al. (2014) reported the distal insertion area as 38.8 ± 38.7 mm^2 and 98 ± 20 mm^2, with Cromeens et al.

(2015) stating the distal attachment area as 140.89 ± 41.93 mm^2 comprising 15.95% of the total bony attachment of deltoid: the PTTL represents 78.03% of the total talar attachment of the MCL (Cromeens et al., 2015).

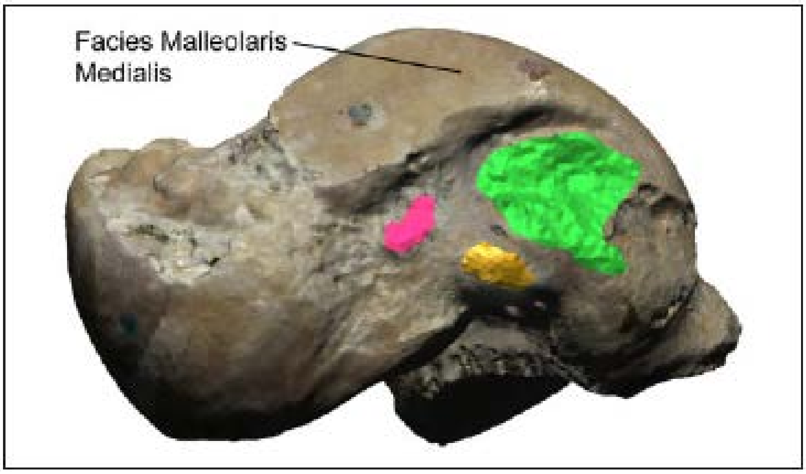

Figure 2.43 The PTTL talar insertion (green) inferior to the facies malleolaris medialis: Pink, ATTL attachment; Orange, STTL attachment (Cromeens et al., 2015).

The length of the PTTL has been measured as 11.86 ± 3.96 mm (Siegler et al., 1988), 26.68 ± 4.49 mm (Mkandawire et al., 2005), 9.5 ± 5.3 mm (Milner and Soames, 1998a), 10.3 mm (Campbell et al., 2014), 10.6 ± 1.0 mm (Luo et al., 1997), 16.8 ± 5.6 mm (Boss and Hintermann, 2002) and 23.6 ± 3.7 mm (Cromeens et al., 2015). Wenny et al. (2014) determined PTTL length differently reporting it as the cranial/posterior and plantar/anterior length, which were 13.44 ± 4.97 mm and 17.74 ± 5.14 mm respectively.

The PTTL was the widest band being 10.4 mm (Panchani et al., 2014), 17 ± 7.1 mm (Milner and Soames, 1998a) and 14.4 ± 1.8 mm (middle width) (Cromeens et al., 2015). Wenny et al. (2014) determind the talar/calcaneal and fibular/tibial width as 9.94 ± 2.97 mm and 8.31 ± 1.9 mm respectively. PTTL thickness was

0.6 mm (Panchani et al., 2014), 2.9 ± 1.1 mm (Butler and Walsh, 2004) and 1.6 ± 0.6 mm (Boss and Hintermann, 2002). MRI has shown that the PTTL is the thickest of all bands of the deltoid complex (Klein, 1994), with MRI based measurement of thickness being 8.2 mm (females: 7.9 mm; males: 8.6 mm) (Mengiardi et al., 2007). PTTL cross sectional area has been reported as 45.2 ± 31.6 mm^2 (Siegler et al., 1988).

2.6.15 Deep Anterior Tibiotalar Ligament (ATTL)

The anterior tibiotalar ligament (ATTL) (Figure 2.41) is part of the deep layer about which there is disagreement in the literature (Milner and Soames, 1998b): it can be absent or poorly defined in some specimens (Pankovich and Shivaram, 1979a). The ATTL has been observed in 93% (Campbell et al., 2014), 86% (Panchani et al., 2014), 66.7% (Cromeens et al., 2015), 50% (Boss and Hintermann, 2002) and 10% (Milner and Soames, 1998b) of specimens, with Milner and Soames (1998b) reporting that it was always observed unilaterally. The ATTL has been observed in 84% of cases in MRI investigations (Klein, 1994); however such images show the ATTL as a thin band (Klein, 1994).

The ATTL is situated deep to the TNL and TSL (Campbell et al., 2014), or deep to the TNL and TCL (Drake et al., 2010a). Pankovich and Shivaram (1979a) observed the ligament as a small band covered by the TCL and may blend with it, even though they had different distal attachments on the talus. The ligament formed an angle of - 6º ± 21° with the long axis of the tibia (Boss and

Hintermann, 2002), running in a forward and downward direction (Palastanga et al., 2006; Pankovich and Shivaram, 1979a).

Discrepancies in describing the ATTL origin have been reported in the literature, with Klein (1994) stating that it originates from the medial malleolus, and Standring (2008) and Cromens et al. (2015) reporting that the proximal attachment is from the tip of the medial malleolus or the most distal part of the anterior colliculus. Milner and Soames (1998b) and Pankovich and Shivaram (1979a) observed the ATTL origin to be from the anterior colliculus and the intercollicular groove of the medial malleolus, while Panchani et al. (2014) reported the proximal attachment being from the medial malleolar anteromedial part distal to the TSL origin and Campbell et al. (2014) from the most distal anterior point of the tibial medial malleolus. The distances between the tibial centre of the deep MCL attachment and the medial malleolar tip and the anterior border of the medial malleolus were 5.89 ± 2.89 mm and 9.3 ± 3.04 mm respectively (Wenny et al., 2014), while the distance between the ATTL origin and distal centre of the intercollicular groove was 11.1 mm (Campbell et al., 2014). The proximal attachment area of the ATTL has been measured as 14.8 ± 14.5 mm^2 (Boss and Hintermann, 2002), 14.85 ± 5.37 mm^2 comprising 1.72% of the total bony attachment of deltoid (Cromeens et al., 2015). Moreover, deltoid comprises 6% of the total tibial attachment (Cromeens et al., 2015). The ATTL was reported to have an anterior, inferior and lateral orientation in the neutral position of the ankle joint (Luo et al., 1997).

The distal insertion of the ATTL (Figure 2.43) has been debated, with some groups stating that it was to the talar medial surface anterior to the PTTL (Cromeens et al., 2015; Standring, 2008; Milner and Soames, 1998b); however various descriptions of the insertion have been reported. The ATTL has been described as inserted distally being anterosuperior to the medial malleolus (Panchani et al., 2014) and distal to the talar articular cartilage (Campbell et al., 2014). Both Wenny et al. (2014) and Klein (1994) reported the distal attachment to be to the neck of the talus, while Palastanga et al. (2006) stated it to be to the medial side of the talar neck, or close to the talar neck as observed by Pankovich and Shivaram (1979a). The distance between the ATTL distal attachment and the anteromedial part of the talar trochlea was 12.2 mm (Campbell et al., 2014), with a distal attachment area of 35 ± 10 mm^2 (Wenny et al., 2014), 25 ± 25.8 mm^2 (Boss and Hintermann, 2002), 20.61 ± 12.71 mm^2 comprising 2.24% of the total bony attachment of deltoid (Cromeens et al., 2015). The ATTL comprises 10.91% of the total talar attachment of the MCL complex (Cromeens et al., 2015).

The ATTL had a length of 24.09 ± 8.03 mm (Mkandawire et al., 2005), 11.5 ± 3.6 mm (Milner and Soames, 1998a), 12 mm (Campbell et al., 2014), 16.1 ± 6.8 mm (Boss and Hintermann, 2002), 19.6 ± 2.2 mm (Luo et al., 1997) and 14.5 ± 3.2 mm (Cromeens et al., 2015). Wenny et al. (2014) reported the cranial/posterior and medial lengths as 8.35 ± 2.31 mm and 11.03 ± 4.12 mm respectively. ATTL width was 6.5 ± 2.5 mm (Milner and Soames, 1998a) and 3.4 ± 0.6 mm (Cromeens et al., 2015), with the thickness being 1.2 ± 0.7 mm

(Boss and Hintermann, 2002), 2.5 ± 0.8 mm (Butler and Walsh, 2004) and 1.2 ± 0.5 mm (Cromeens et al., 2015).

2.6.16 Band Deep to TCL (dTCL)

The band deep to the TCL (dTCL) (Figure 2.44) is a component of the deep layer of the deltoid ligament, but has only been reported in one investigation (Panchani et al., 2014), being observed in 4 of 33 specimens (12%) and always unilateral. The dTCL originated from the medial malleolar tip between the ATTL and PTTL proximal attachments and inserted distally to the talar superomedial part between the ATTL and PTTL attachments; the dTCL thickness was measured as 0.81 mm (Panchani et al., 2014).

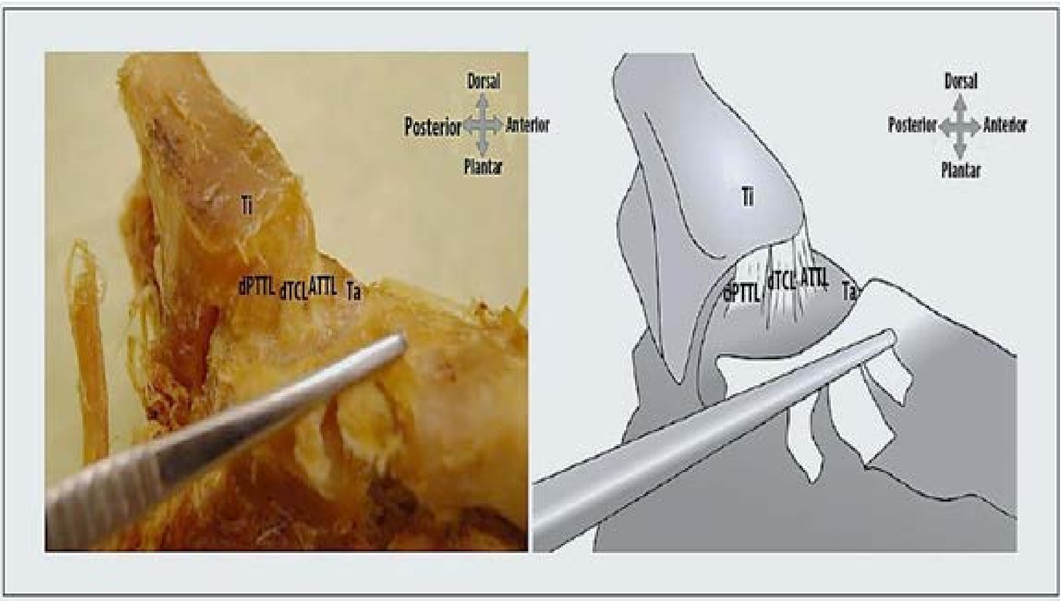

Figure 2.44 Band deep to the TCL (dTCL) shown as a part of the deep layer of the deltoid ligament: dPTTL, deep posterior tibiotalar ligament (PTTL); TI, tibia; Ta, talus (modified from Panchani et al., 2014).

2.6.17 Inferoplantar Longitudinal Ligament

The inferoplantar longitudinal ligament (Figure 2.45) is the only band in the plantar area which has been suggested to be part of deltoid (Cromeens et al., 2015). It was lateral to the tibiocalcaneonavicular ligament, which previously was known as the inferoplantar longitudinal part of the spring ligament, and was consistent in occurrence, running in an anteromedial direction before inserting into the navicular beak. The ligament had a length, width and thickness of 15.9 ± 3 mm, 5.2 ± 1.3 mm and 1.7 ± 0.6 mm respectively (Cromeens et al., 2015).

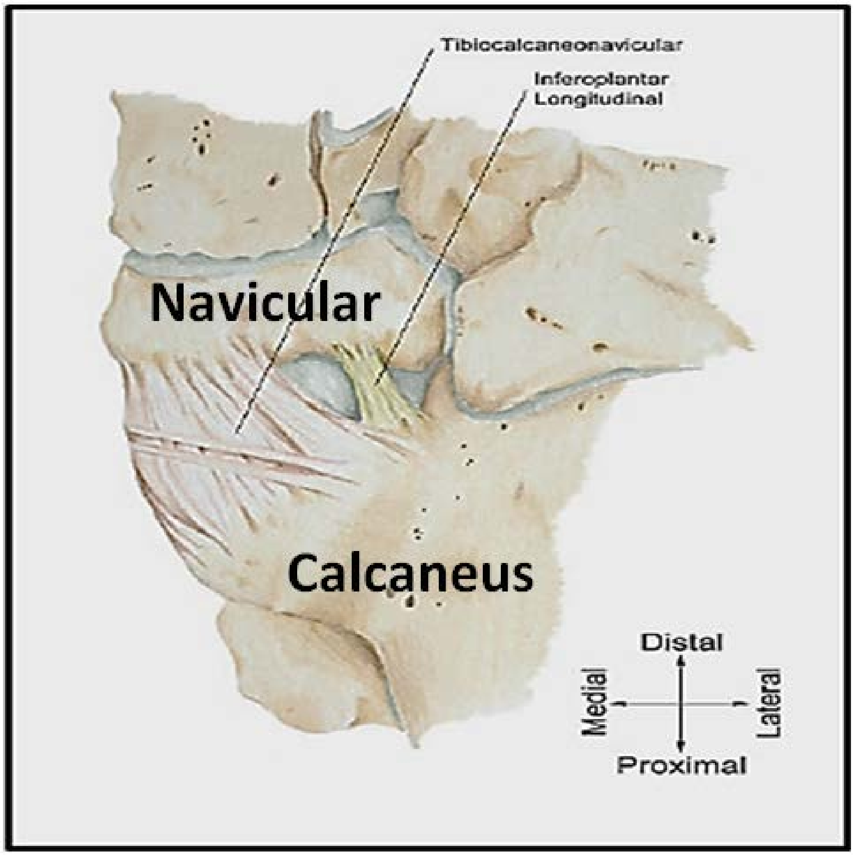

Figure 2.45 The inferoplantar longitudinal ligament (Cromeens et al., 2015).

2.7 Role of the Ankle Collateral Ligaments

2.7.1 Strain at the Ankle Lateral and Medial Collateral Ligaments

Different parts of the lateral and medial collateral ligaments are under strain in different positions of the ankle and subtalar joints. The ATFL was observed to be taut in plantarflexion and relaxed in dorsiflexion (Miller and Thompson, 2015; Sarrafian, 1993a). In the two band form the superior band is taut in plantarflexion and the inferior band in both dorsiflexion and plantarflexion (Vogel, 1970: as cited by Sarrafian, 1993a). In addition, the ligament is reported to be under tension in inversion and internal rotation (Colville et al., 1990). The ATFL was found to have 3.3% strain from 10° dorsiflexion to 40° plantarflexion (Renstrom et al., 1988). Buzzi et al. (1993) reported an 8.9% change in the distance between origin and insertion of the ATFL proximal fibres in plantarflexion. Supporting the above observations Raheem and O'Brien (2011) reported length changes in the ATFL with the ankle in neutral, dorsiflexion and plantarflexion as 15.5 ± 7.7 mm, 14.5 ± 6.3 mm and 18 ± 9.8 mm respectively.

The CFL is stretched in ankle dorsiflexion and inversion (Bahr et al., 1998; Cawley and France, 1991) and additionally in external rotation (Nigg et al., 1990). However, Sarrafian (1993a) indicated that the CFL is generally taut in dorsiflexion and relaxed in plantarflexion, but in some cases it is less tense in dorsiflexion and taut in plantarflexion: occasionally the tension does not change. In addition, the CFL is relaxed in inversion and stretched in eversion, with the variability in CFL tension being the result of variations in its insertion (Sarrafian, 1993a), as well as being due to its shape and orientation, i.e. oblique, horizontal, vertical or fan shaped (Ruth, 1961). The CFL was found to be under strain in inversion, but decreased as the range of plantarflexion increased (Renstrom et al., 1988). Moreover, in dorsiflexion the distance between the origin and insertion of the CFL anterior, central and posterior fibres increased by 3.4%, 8.5% and 16.9%respectively (Buzzi et al., 1993); additionally, Raheem and O'Brien (2011) found the CFL length to be 18.5 ± 6.3 mm (neutral), 15.5 ± 6.3 mm (dorsiflexion) and 17 ± 5.6 mm (plantarflexion). Therefore, the increased distance between the origin and insertion results in a stretched CFL; thus if it is vertical in neutral, it will be less stretched in eversion and taut in inversion (Sarrafian, 1993a). Moreover, Colville et al. (1990) suggested that the ATFL and CFL work together in all ankle movements to prevent lateral ankle instability.

The PTFL is under higher strain in dorsiflexion compared to plantarflexion (Ozeki et al., 2002) as a consequence of the distance between origin and insertion of its long fibres increasing by 12.2% in dorsiflexion. The anterior part of the PTFL is taut in all positions, while its posterior part is only taut in dorsiflexion (Vogel, 1970: as cited by Sarrafian, 1993a).

The tibionavicular (TNL), anterior tibiotalar (ATTL) and the majority of the tibiocalcaneal (TCL) fibres are taut in plantarflexion. On the other hand, the superficial tibiotalar (STTL) and posterior deep tibiotalar (PTTL), as well as the posterior fibres of the TCL, are taut in dorsiflexion (Pankovich and Shivaram, 1979a).

The ligament zero strain (ligament zero load length) was defined by Tochigi et al. (2005) as the point when the ligament starts to become stretched and resist a specific movement; however, Kleipool and Blankevoort (2010) defined this point as the length of the ligament when it is most slack and has the shortest length, indicating that the ligament is not functioning. When the strain is greater than zero it means that the ligament is functioning and loaded, while if it is less than zero the ligament is shortened and not functioning (Kleipool and Blankevoort, 2010).

A number of studies have investigated strain changes and loading during different movements. Attarian et al. (1985a) applied different loads to the different ligaments, obtained from amputations with no ankle pathology, to determine the level of failure without considering the presence of other ligaments. They found the ATFL to be the weakest, failing at 138.9 N, while the deep component of the deltoid ligament was the strongest with a load to failure of 713.8 N: the loading was applied to only six specimens as in many cases the medial malleolus fractured before the ligament failed. The CFL and PTFL were completely disrupted with loads reaching 345.7 N and 261.2 N.

Siegler et al. (1988) reported that the ATFL had a maximum elongation of 2.46 ± 0.76 mm, being the weakest ligament due to its low ultimate load (231 ± 142 N), as well as being anterior to the ankle. Maximum elongation of the CFL was 3.66 ± 0.71 mm and was found to be one of the strong ligaments with a high ultimate load (307 ± 142 N): this is probably due to its density and the axial orientation of its fibres. The PTFL stretched 3.48 ± 0.94 mm with a high ultimate load of 418 ± 199 N. It has been concluded that the mediolateral orientation of the deltoid fibres and its position allows it to provide the appropriate restriction to dorsiflexion and prevent the talus from being laterally or posteriorly displaced. However, the TCL was, surprisingly, not as important in providing support to the ankle as it had a low ultimate load (< 44.5 N), while the TSL was the strongest superficial part with a high ultimate load (432 ± 307 N) making it an important supporter even though it has been rarely described in the literature. Its maximum elongation was 6.48 ± 1.4 mm, which may be linked to its distal insertion being to the spring ligament. Furthermore, 3.1 ± 0.81 mm was the maximum elongation of the PTTL, which is considered to be the thickest, stiffest ligament of all the collateral ligaments with a high ultimate load (467 ± 209 N), with males demonstrating a significantly higher ultimate load than females ($P = 0.032$) (Siegler et al., 1988).

In 1990, Nigg et al. investigated three fresh frozen ankles under physiological loading between 0° to 15° dorsiflexion, plantarflexion, inversion, eversion, internal and external rotations; however, the ankles were dissected and the surrounding tissues removed, while the ROM was not a simulation of the full functional range as in the living. The ATFL was found to be most taut in maximum plantarflexion and internal rotation, while the CFL and superficial deltoid were most stretched in dorsiflexion, inversion, internal rotation and dorsiflexion and external rotation respectively. The force to failure were 130 ± 63 N for the ATFL, 296 ± 31 N for the CFL and 244 ± 271 N for the superficial deltoid. Bahr et al. (1998) examined eight dissected fresh cadaveric feet using a transducer system that loaded different ligaments: the ATFL was longest in inversion and plantarflexion at a compressive load of 76 ± 23 N, while the CFL was most taut in inversion and dorsiflexion at a compressive load of 109 ± 28 N. In another investigation the strength of the PTTL was reported as 446 ± 51 N in applied tension on 10 fresh frozen cadaveric ankles (Annechien Beumer et al., 2003).

Luo et al. (1997) investigated different joint positions comparing them to neutral, with the greatest change in ATFL in plantarflexion (5 ± 2.7 mm), being smaller in both anterior drawer and inversion (0.1 ± 1.8), while there was significant elongation between plantarflexion and both dorsiflexion and eversion. The CFL had the largest elongation in inversion (5.1 ± 2.9 mm) and dorsiflexion (1.9 ± 0.8 mm), with a small change in plantarflexion and eversion: a significant change was observed between elongation in inversion and all other positions. Minor elongation in the PTFL was observed, being greatest in anterior drawer and smallest in inversion (0.5 ± 1.9 mm). A significant change was observed between inversion and both anterior drawer and dorsiflexion. The TNL was elongated in plantarflexion (5.6 ± 0.41 mm), anterior drawer and eversion (1.9 ± 1.9 mm): there was a significant change between plantarflexion and both dorsiflexion and inversion. In addition, there was no change in TCL length in plantarflexion, while dorsiflexion had a change of 2.6 ± 1.1 mm and eversion 1.8 ± 0.8 mm. PTTL elongations were 3.5 ± 2.4 mm for dorsiflexion, 1.5 ± 1.5 mm for eversion and 1.0 ± 2.0 mm for inversion, with the elongation between dorsiflexion and inversion being significant.

Ozeki et al. (2002), using a strain transducer system, found that ATFL length increased in plantarflexion and decreased in dorsiflexion with the zero strain reference being at 16° ± 3º plantarflexion with the length (L0) being 0.64 ± 0.32 mm greater than that in neutral (Ln); in their study the zero strain reference was determined when the ligament starts its resistance to a movement. Between 40° plantarflexion and 10° dorsiflexion elongation significantly decreased. The maximum change in length was 1.56 ± 0.76 mm (7.9% ± 3.66%). CFL length decreased in plantarflexion and increased in dorsiflexion with the zero strain reference at 18° ± 6º dorsiflexion and length 0.94 ± 0.31 longer than Ln. Between 10° plantarflexion and 30° dorsiflexion the strain was significantly increased. The maximum change in length was 1.47 ± 0.65 mm (5.3% ± 2.47%). In addition, PTFL elongation increased in dorsiflexion and decreased in plantarflexion with 18° ± 8° dorsiflexion being the zero strain reference at a length 0.67 ± 0.38 mm greater than at Ln. Between 10° plantarflexion and 30° dorsiflexion elongation significantly increased. The maximum length change was 1.17 ± 0.41 (5.9% ± 2.37%). Moreover, the maximum TCL strain was at neutral with the length decreasing toward both dorsiflexion and plantarflexion: the TCL L0 of 0.28 ± 0.32 mm was shorter than Ln at 10° ± 9° plantarflexion. Between 40° plantarflexion and 10° dorsiflexion an increase in strain was observed with the maximum change in length being 1.5 ± 0.69 mm (5.2% ± 2.62%).

2.7.2 Isometric Characters of the Ankle Collateral Ligaments

The isometric characteristic of a structure is considered when the structure is functions without changing length; for example isometric muscle contraction

(Hall, 2016); or no change in a ligament length during a joint movement (Victor et al., 2009); therefore, a ligament is isometrically restricting a joint motion when the ligament has no change in length (strain). In reconstruction procedures of injured ligaments, it is important to understand the isometric characteristics of the ligament (Helito et al., 2014, Victor et al., 2009). This may help to produce better isometric grafts from the reconstruction procedures of injured ligaments (Sidles et al., 1988).

According to Bruns and Rehder (1992) the CFL and TCL have isometric characteristics, with the CFL being isometric in neutral without any strain observed (Renstrom et al., 1988). However, the ATFL generally has an anisometric character for many fibres, with no significant strain difference being observed from neutral; however, the anterior ATFL fibres were most strained in maximum plantarflexion, while the posterior fibres were less strained. Buzzi et al. (1993) studied the distances between the proximal and distal attachments of the LCL and reported that the distance between the ATFL proximal fibres increased significantly (8.9%) in plantarflexion, but there was no change in the central and distal fibres, these being isometric.

2.7.3 Transection of the Ankle Collateral Ligaments

2.7.3.1 Lateral Collateral Ligaments

A number of studies have examined the effect of transection of one or more ligaments of the LCL. ATFL sectioning leads to increased anteroposterior laxity of the ankle in dorsiflexion, inversion and eversion (Johnson and Markolf, 1983). Cass et al. (1984) reported that releasing the ATFL at 30° plantarflexion results in a 30% increase in tibial adduction and an 8% increase in tibial external rotation. Applying anterior-posterior and inversion-eversion loading after sectioning the ATFL leads to an increase in dorsiflexion, with subtalar movement also increasing (Hollis et al., 1995). Disturbing the ATFL causes inversion and anterior instability of the ankle (Shibata et al., 1986), as well as causing talar tilt, which is marked at plantarflexion, with a minimal increase in dorsiflexion and plantarflexion (0.5° – 2°), an increase in adduction but no change in abduction (Rasmussen, 1985). Releasing the CFL at 15° plantarflexion produced 10% and 3% increases in tibial adduction and external tibial rotation respectively (Cass et al., 1984); however, Rasmussen (1985) reported an increase in adduction only. In addition, Kjœrsgaard-Andersen et al. (1987b) observed that transecting the CFL caused a significant increase in hindfoot internal or external rotation. The CFL has a role in subtalar loading such that when disrupted a significant increase in elongation of the cervical ligament occurs, which may affect the stability of subtalar movements (Martin et al., 1998; Martin et al., 2002). Sectioning the PTFL produced a slight increase in external rotation and dorsiflexion, but no change in adduction, abduction or plantarflexion (Rasmussen, 1985).

Disturbing both the ATFL and CFL in neutral resulted in an increase in tibial adduction (41%) and external rotation (65%) (Cass et al., 1984). Rasmussen (1985) also reported an increase in adduction, but not much compared to when only the ATFL was sectioned. An additional increase in internal rotation was found, but no change in abduction or external rotation. Thus disturbing the ATFL and CFL leads to adduction instability at the ankle and subtalar joints

(Shibata et al., 1986). However, sectioning the CFL after sectioning the ATFL did not result in an increase in ankle movements (Erduran and Havıtçıoğlu, 2011), although Hollis et al. (1995) reported that dorsiflexion was affected by the combined ATFL and CFL sectioning. When the ATFL and CFL are disrupted, the PTFL anterior short fibres limit dorsiflexion, talar tilt and internal and external talar rotation, while its posterior long fibres limit dorsiflexion, talar tilt and external rotation (Rasmussen et al., 1983b).

Disturbing the CFL with the PTFL short fibres leads to an increase in adduction, while disturbing the CFL with the PTFL long fibres results in an increase in adduction, external rotation and dorsiflexion, but no change in abduction and internal rotation. In addition, combined sectioning of the ATFL, CFL and PTFL produced increases in adduction, internal rotation, dorsiflexion (13°), with minimal increases in plantarflexion (1°) and no increase in abduction (Rasmussen, 1985). Cass et al. (1984) reported a 41% increase in tibial adduction and a 240% increase in external tibial rotation. When the ATFL was sectioned internal rotation increased from 7 to 18° and up to 21° if there is also disruption in the CFL (Rasmussen and Tovborg-Jensen, 1982).

Studies have shown that sectioning the LCL increased dorsiflexion and internal rotation, especially in plantarflexion, and talar external rotation, especially in dorsiflexion (Palastanga et al., 2006). Moreover, in an *in vitro* study by Rasmussen and Tovborg-Jensen (1982) no significant changes in dorsiflexion were observed if only one LCL ligament was injured, but when all the LCL were disrupted dorsiflexion increased from 18° to 28°; however, there was no change in plantarflexion when sectioning one or all of the LCL components. In addition, they reported no change in talar external rotation in isolated sectioning one component of the LCL; however, when all LCL ligaments were completely disrupted, rotation increased from 10° to 19°, being most marked in dorsiflexion. Cass et al. (1984) found that motion at the subtalar joint was not affected by sectioning the LCL.

2.7.3.2 Medial Collateral Ligaments

Sectioning the TCL resulted in an increase in abduction and external rotation in dorsiflexion and plantarflexion (4%) (Kjærsgaard-Andersen et al., 1989), but not in talar tilt (Earll et al., 1996). When both the ATFL and CFL were disturbed, the TCL worked as a lateral stabiliser resisting inversion (Ziai et al., 2015). Rasmussen (1985) reported increased abduction in combined TCL-TSL, TCL-anterior part of PTTL sectioning, but no change in dorsiflexion, plantarflexion, internal or external rotation in combined sectioning of TCL-TSL and TCL-TSL-ATTL. However, combined transection of the TCL, TSL, ATTL and the anterior part of the PTTL led to increases in abduction, dorsiflexion, plantarflexion, external rotation and internal rotation (slight). Furthermore, sectioning the TCL and PTTL caused extreme instability, with extreme increases in abduction, internal and external rotation and dorsiflexion, but not in plantarflexion. Transection of the TCL, ATTL and PTTL produced a lax ankle, while transecting the TCL-TSL and ATTL produced little change in abduction compared to when only TCL-TSL were sectioned.

Disrupting the TNL and TSL resulted in the subtalar joint being unlocked granting a further range of eversion resulting in laxity of the ATFL. In addition, sectioning the PTTL increased the distance of the PTTL posterior border between its origin and insertion: the TNL increased in length at rest and eversion and decreased in dorsiflexion. Sectioning the superficial layer of deltoid showed no change in PTTL length, but increased the distance along the anterior and posterior borders of the superficial deltoid and between its origin and insertion in all positions except dorsiflexion (Quiles et al., 1983). In addition, talar external rotation increased when the superficial deltoid ligament was disrupted (Padovani, 1975; as cited by Rasmussen et al., 1983a).

Quiles et al. (1983) conducted a study that involved cutting the superficial deltoid with the PTTL, which led toto an increase in the distance of the PTTL posterior border and between the PTTL origin and insertion at rest, plantarflexion, eversion and abduction. In addition, there was an increased distance along the posterior line of the superficial deltoid and between the superficial deltoid origin and insertion in all positions, as well as increasing the distance along the anterior border of the superficial deltoid between its origin and insertion at rest, abduction, eversion and plantarflexion. Furthermore, transection of the superficial deltoid with the ATTL resulted in an increase in the distance along the anterior border of the superficial deltoid and between the origin and insertion of the superficial layer in all joint positions. Moreover, sectioning the whole deltoid increased the distance along anterior and posterior borders of the superficial deltoid and between its origin and insertion in all positions except dorsiflexion, and increased the distance along posterior border of PTTL between its origin and insertion in all positions except dorsiflexion (Quiles et al., 1983).

Sasse et al. (1999) demonstrated that disrupting the deltoid ligament resulted in a significant decrease in talar external rotation in dorsiflexion, as well as talar internal rotation in plantarflexion. Investigating the ankle ligaments using sequential transection of the ligament while applying different loads may not give an accurate reflection of the ligament’s function, as evidenced by the inconsistent outcomes. In addition, sectioning different bands after cutting others risks accuracy, which may give false indications of the cause of the greatest instability (Hintermann and Golanó, 2014). Stormont et al. (1985) demonstrated that the results only depend on the order of ligament transection.

2.7.4 Function of the Ankle Collateral Ligaments

2.7.4.1 Lateral Collateral Ligaments

The ATFL works mainly to restrict ankle plantarflexion (Palastanga et al., 2006; Rasmussen, 1985; Rasmussen et al., 1983a) and to limit inversion (Bahr et al., 1998; Kaneko, 1985), especially in plantarflexion (Nordin and Frankel, 2001). Moreover, the ATFL helps spread inversion tension from the lateral malleolus to the calcaneus and navicular (Kapandji, 1989). In addition, it limits eversion in neutral, plantarflexion and dorsiflexion (Leardini et al., 2000), lateral talar tilt (Sarrafian, 1993a) and talar anterior displacement (Nordin and Frankel, 2001;

Rasmussen, 1985). Furthermore, the ATFL has a role in limiting adduction (Kaneko, 1985), especially in plantarflexion (Rasmussen, 1985), and in controlling talar internal rotation (Hockenbury and Sammarco, 2001). The ATFL restricts varus tilt in dorsiflexion and plantarflexion being the main ankle stabiliser (Palastanga et al., 2006), although Bulucu et al. (1991) reported that the LCL components work together and none can be considered to be the main stabilizer. Additionally, the ATFL is responsible, when standing on tip toes, for resisting anterior movement, medial rotation and lateral tilt of the talus: it also has a role in limiting external rotation of the fibula and resisting posterior shift of the tibia (Sarrafian, 1993a).

The CFL acts on both the ankle and subtalar joints (Sarrafian, 1993a) restricting eversion in neutral, dorsiflexion and plantarflexion (Leardini et al., 2000), as well as helping to spread eversion tension from the lateral malleolus to the calcaneus (Kapandji, 1989). Stephens and Sammarco (1992) demonstrated that the CFL stabilises the ankle in all position, with the ligament considered as one of the important stabilisers of subtalar movement (Weindel et al., 2010; Sarrafian, 1993b; Kjaersgaard-Andersen et al., 1987a) suggesting the importance of reconstructing the CFL when injured (Weindel et al., 2010). Moreover, Nordin and Frankel (2001) reported that the CFL limits inversion in dorsiflexion. It was found to inhibit talar adduction (Palastanga et al., 2006; Kaneko, 1985), particularly in neutral and dorsiflexion (Rasmussen, 1985). The ATFL and CFL function in harmony as they both limit talar tilting as the ATFL becomes vertical in plantarflexion preventing talar tilt, while the CFL becomes more vertical in dorsiflexion and prevents talar tilt (Sarrafian, 1993a).

The PTFL has an important role in limiting ankle dorsiflexion (Palastanga et al., 2006; Valmassy, 1996) and helps in transferring eversion tension from the lateral malleolus to the talus (Kapandji, 1989). In addition, it has a role in preventing posterior talar displacement (Sarrafian, 1993a): this happens in cooperation with the CFL (Harper, 1989). The PTFL resists anterior movement and talar external rotation, as well as limiting anterior movement of the leg and internal rotation of the fibula and tibia (Sarrafian, 1993a). Stephens and Sammarco (1992) suggested that the PTFL stabilises the ankle in all joint positions; however, Rasmussen (1985) demonstrated that it is not an independent ankle stabiliser, its action being supplementary to the ATFL and CFL in ankle stabilisation (Rasmussen et al., 1983b). According to Leardini et al. (2000) all LCL components limit eversion when the ankle is dorsiflexed.

2.7.4.2 Medial Collateral Ligaments

The medial collateral ligament is the most critical structure in inhibiting talar lateral shift and limiting talar external rotation (Nordin and Frankel, 2001): it also restricts eversion (Firestein et al., 2013; Harper, 1987). The deltoid is antagonist to the LTCL, which limits inversion and talar internal rotation (Firestein et al., 2013). In addition, the posterior aspect of the deltoid complex limits ankle dorsiflexion (Valmassy, 1996), while the deep component is considered a secondary restrictor for anterior and lateral shift (Harper, 1987). The deep deltoid has many roles in limiting dorsiflexion, inhibiting talar shift and internal rotation (Sarrafian, 1993a). The deltoid, with the help of the spring ligament, plays an important role in hindfoot stabilisation and passive movement guidance

(Hintermann and Golanó, 2014). In addition, the posterior part of deltoid plays a role in spreading inversion tension from the medial malleolus, while the anterior part of the superficial deltoid helps in spreading eversion tension from the medial malleolus to the navicular and calcaneus (Kapandji, 1989).

The TCL restricts talar abduction (Palastanga et al., 2006; Kjærsgaard-Andersen et al., 1989), with Wirth et al. (1978) reporting that it limits plantarflexion, while Kjærsgaard-Andersen et al. (1989) demonstrated that the TCL and TSL inhibit dorsiflexion (as cited by Rasmussen et al., 1983a). In addition, the TCL limits eversion (Sarrafian, 1993a) and external rotation (Kjærsgaard-Andersen et al., 1989), as well as stabilising the talus medially. One additional function of the TCL is the support it provides to the subtalar joint (Sarrafian, 1993b). The TNL limits plantarflexion, talar external rotation (Sarrafian, 1993a) and talar abduction (Palastanga et al., 2006). The TSL supports the spring ligament against gravity and pressure from the head of the talus: in addition part of the tibialis posterior tendon supports the spring ligament (Sarrafian, 1993a). The ATTL restricts plantarflexion (Palastanga et al., 2006) working with the PTFL, ATFL and TNL (Rasmussen et al., 1983a).

PTTL function is to limit ankle dorsiflexion (Palastanga et al., 2006): the anterior part also restricting talar abduction, dorsiflexion, internal and external rotation (Rasmussen, 1985). According to Rasmussen et al. (1983a) the posterior part of the PTTL restricts only talar abduction, disagreeing with a later publication (Rasmussen, 1985) which demonstrated that the posterior aspect of the PTTL plays a role in restricting dorsiflexion and possibly also internal rotation.

The ankle ligaments have been reported to have no mechanical role during ankle or subtalar motion (Kleipool and Blankevoort, 2010; Haraguchi et al., 2009; Tochigi et al., 2005), especially when the range of motion is within the FROM during normal activities (Kleipool and Blankevoort, 2010). The ligaments seem to be secondary supporters to the ankle against extreme ranges of motion (Tochigi et al., 2005). The deltoid is reported to be more important during ankle motion; however the ATFL may have a role in transferring some of the load from the fibula to the talus, while the PTFL is mostly involved in transferring forces in dorsiflexion during the stance phase. The CFL was not found to receive or bear any load (Haraguchi et al., 2009). Stability of the ankle joint during full loading depends on the articular surfaces, which limit even inversion displacement. In addition, internal rotation of the leg is restrained by the ATFL, which works more in plantarflexion, while deltoid is the predominant restrictor in neutral and dorsiflexion: external rotation is restricted by the CFL. Inversion and eversion are restrained primarily by the CFL and deltoid respectively (Stormont et al., 1985).

2.7.5 Sensory function of the ankle ligaments

In 1900, Pyar hypothesised a sensory function of the ligaments (as cited by Kleipool and Blankevoort, 2010). In a histological study of cat knees Freeman and Wyke (1967) classified 4 types of articular nerve endings: type I, II and III were mechanoreceptors, while type IV included nerve endings that could be either pain receptors or visceral efferents. In a histological investigation of the human LCL Moraes et al. (2008) reported that the ATFL, CFL and PTFL contained free nerve endings and mechanoreceptors. Wu et al. (2015)

confirmed that the LCL has all four types of mechanoreceptors with type II being predominant, which helps in sensing ankle movement. In an earlier study Michelson and Hutchins (1995) demonstrated that the ankle ligaments have type II and III mechanoreceptors, which are responsible for providing sensation at the beginning of movement and the end of the range of movement respectively: type I was also seen but in small quantities. Therefore, injuries to the ankle ligaments may cause a loss of proprioception, resulting in the need for proprioception training following injury and/or reconstruction to retain function.

2.8 Ankle Collateral Ligaments Injuries (Clinical Aspects)

2.8.1 Epidemiology

In the USA, there is one ankle sprain incidence per 10000 people every day, with the total number of ankle sprains 28000 per day (Adams et al., 2013): in the UK there are approximately 5000 cases reported per day (Geppert, 1998; as cited by Kumai et al., 2002). Eighty five percent of ankle sprains result in an injury to the lateral collateral ligament (Ferri, 2016; Adams et al., 2013), with 65% affecting the ATFL alone (Adams et al., 2013). Sports like indoor wall climbing, mountaineering, aeroball and track and field events have ankle injuries as the most common injury, with ankle sprains being the most common. In addition, ankle sprains were the most regular injury to players of team sports such as basketball, soccer, netball (Bortzman and Manske, 2011), handball, rugby and volleyball (Fong et al., 2007). In addition, Yeung et al. (1994) reported that 73% of Hong Kong athletes have had a recurrent ankle sprain, with a significant proportion resulting in a disability or symptoms that affected their performance.

Gerber et al. (1998) reported that injuries to the LCL, deltoid (MCL) and syndesmosis ligaments (tibiofibular) compose 79.17%, 4.17% and 16.67% of ankle sprains respectively, while Waterman et al. (2011) reported that 11.8% of ankle sprains result in injury to the syndesmotic and deltoid ligaments (Bortzman and Manske, 2011). In addition, an ankle sprain is not just a common injury in sport; it is also one of the most common injuries in dancers (Russell, 2010). Moreover, there is no difference between males and females in the incidence of ankle sprains (Waterman et al., 2010; Beynnon et al., 2002);

however, Doherty et al. (2014) observed that ankle sprains were more common in females (13.68 per 1000 exposure) than males (6.94 per 1000 exposure). Furthermore, they reported that there were significantly more in children than adolescents, and more in adolescents compared to adults. Cameron et al. (2010) reported that those in the military had an ankle sprain incidence rate 5 times greater than the public, with females having 21% more ankle sprains. Older people were found to have a lower rate of ankle sprain with the risk increasing with being younger: soldiers younger than 20 years old had the highest incidence of ankle sprains.

Deltoid ligament injury is not common usually occurring when there is a fracture to the medial malleolus (Adams et al., 2013). High competitiveness and being male are risk factors to syndesmotic and medial ankle sprains. In addition, most medial ankle sprains in sport are associated with soccer, gymnastics and rugby (Waterman et al., 2011)

2.8.2 Mechanism of Injury

Understanding the mechanisms of injury that cause ligament tears is important to help clinicians understand fracture type and/or the soft tissues affected (Okanobo et al., 2012). An ankle sprain is usually due to an inversion (Adams et al., 2013) or plantarflexion injury (Ferri, 2016) and may involve the anterior joint capsule (Browner et al., 2015), while injury to the deltoid or anterior tibiofibular ligaments or interosseous membrane is due to an eversion or rotational movement (Ferri, 2016). Joint flexibility (laxity) is reported have no relationship to joint injury incidence (Jackson et al., 1977), although Browner et al. (2015)

have indicated that excessive laxity of the subtalar joint may cause lateral ankle instability. It has been reported that 36% of individuals with an ankle sprain have had a previous injury to the same ankle (Bosien et al., 1955).

Ankle sprains are seen less in barefoot activities, probably resulting from the accurate sensation of the joint position compared to wearing footwear, which may impair the sensation of joint position (Robbins and Waked, 1998). Therefore, ankle sprains may result from unexpected placement of the foot on different surfaces or in the air before landing: this supports the proprioception theory as a factor in an inversion sprain. Moreover, Clark et al. (1986) indicated that articular and capsule receptors do not play a significant role in providing awareness of joint position: this is supported by total joint replacement which usually is not affected (as cited by Robbins and Waked, 1998). In addition, sensory input from muscles and plantar tactile receptors reported to play the most important roles in sensing ankle joint position (Clark et al., 1985). Therefore the resulting impairment of sensing joint position in patients with ankle instability increases the risk of sustaining a new injury (Konradsen, 2002). Moreover, it has been reported that 54% of volleyball injuries are ankle sprains resulting from technical errors during landing: 79% of the sprained ankles had had a previous ankle sprain (Bahr and Bahr, 1997).

Kofotolis et al. (2007) observed 312 male soccer players (amateur) over a 2 year period and reported 139 cases of ankle sprains, with defenders (42.3%) and midfielders (32.6%) having the highest incidence: 68.3% of injuries were on the dominant side and 60.5% of patients had a previous ankle injury. An ankle sprain results in injury to the ATFL (62.59%), deltoid (15.83%), anterior tibiofibular (5.76%), CFL (3.6%) and PTFL (3.6%): 8.63% of cases were not specified. The sprain was caused by a contact injury in 63.31%, with the majority (79.31%) being from player to player contact: other contact injuries included player to floor and ball contact injuries. In addition, 36.69% of ankle sprains resulted from non-contact injuries, including landing (25.49%), twisting (21.57%) and running (11.76%).

2.8.2.1 Lateral Collateral Ligaments

A sprained ankle commonly affects the ATFL, with the CFL being the second to be injured and commonly combined with an ATFL injury (Bortzman and Manske, 2011). No weakness was found in the invertor muscles in patients with ankle sprains or instability (Willems et al., 2002). In addition, tears of the ATFL and CFL usually occur in the midsubtance: proximal and distal bony avulsion of the ligaments may also occur (Coughlin et al., 2014). Broström (1966) demonstrated that ATFL tears occur at the mid region or near the lateral malleolus in 28.33% and 36.67% respectively, while the ATFL was found to be torn in an avulsion fracture of the lateral malleolus and talus in 33.33% and 1.67% of cases respectively. It is not common to have an isolated injury to the CFL (Adams et al., 2013; Robbins and Waked, 1998; Francillon, 1962). Similarly a PTFL injury is rarely seen (O'Loughlin et al., 2009), when the PTFL sustains a partial or complete tear the ATFL and CFL are always involved (Broström, 1964).

Lateral ankle sprain may result from fracture of the talar lateral process or calcaneal anterior process (Browner et al., 2015). In addition, a lateral malleolar avulsion fracture may cause an ankle sprain (Browner et al., 2015), this especially occurs in lateral malleolar fractures such as in a supination-adduction fracture that causes widening of the lateral ankle mortise which usually causes tears in the ATFL and CFL (Okanobo et al., 2012). Meyer et al. (1988) reported that 42% of patients with ankle sprain also had a fragment or fracture to the proximal attachment of the ligaments. An inversion injury appears to be more complex than previously thought: Khor and Tan (2013) found that only 22% of patients had an isolated lateral ligament injury, while a further 22% had other pathologies but no injury to the LCL: 53% of patients had an LCL injury combined with other injuries or conditions. Considering all patients there was bone bruising (50%), tendon pathology (30%), deltoid injury (27%) and an occult fracture (22%).

Fracture of the lateral process of the talus usually occurs during snowboarding (Browner et al., 2015), therefore the ATFL, PTFL and LTCL may be affected as they are attached to the lateral process (Figure 2.46) (DiGiovanni et al., 2007). Moreover, it has been reported that a 1 cm^3 fragment fracture from the lateral talar process results in a loss of 100% and 10% - 15% of the LTCL and both talofibular ligaments (ATFL and PTFL) respectively (Browner et al., 2015), although Langer et al. (2007), using stress radiographs after lateral talar process fracture, reported no effect on ankle or subtalar stability.

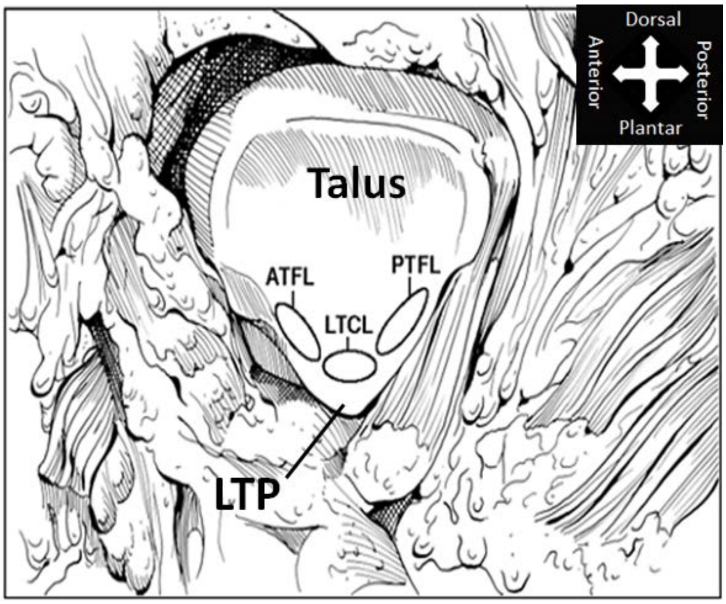

Figure 2.46 Attachments of ATFL, PTFL and TCL to the lateral talar process: LTP, lateral talar process; ATFL, anterior talofibular ligament; PTFL, posterior talofibular ligament; LTCL, lateral talocalcaneal ligament (modified from DiGiovanni et al., 2007).

Talar neck fracture is a rare injury (Browner et al., 2015) frequently resulting from road traffic accidents or falling from a height. The mechanism of injury involves a dorsiflexion force, although one case has been reported with a plantarflexion and inversion force (Kenwright and Taylor, 1970). Sneppen and Buhl (1974) have suggested that inversion, eversion, and inversion with external rotation all contribute to such a fracture. Baumhauer et al. (1995) proposed that muscle imbalance, such as plantarflexion being stronger than dorsiflexion, or an elevated eversion-inversion ratio increases the risk of sustaining an ankle sprain.

The ATFL is usually repaired after surgery to fix talar body fractures as surgeons need to perform a fibular osteotomy to reflect the fibula and fix the fracture. In addition, the CFL is excised during open reduction and internal fixation surgery, such as in the sinus tarsi approach in calcaneal comminuted fractures (Browner et al., 2015).

2.8.2.2 Deltoid Ligament

The most common mechanism of injury of the deltoid ligament is eversion trauma in which the foot is laterally rotated while the tibia is medially rotated (Hintermann et al., 2004). This can be caused by very high external loads or forces (Robbins and Waked, 1998) or a complex injury to the ankle (Savage-Elliott et al., 2013). Furthermore, injury may result from a lateral malleolar fracture (Koval et al., 2007). A partial tear of the deltoid may occur without fracture, while a complete tear is usually seen in combination with a fibular or tibiofibular fracture (McConkey et al., 1991). However, in one case report the patient had an isolated complete tear of the anterior part of the deltoid without involvement of the LCL or any fracture (Jackson et al., 1988). Injuries that cause a medial malleolar fracture, medial widening of the ankle mortise or those that result from a pronation external rotation fracture are usually accompanied by a deltoid ligament rupture (Okanobo et al., 2012). Extreme talar neck fractures can also cause deltoid rupture (Browner et al., 2015).

Deltoid injury may occur in combination with pathology of the tibialis posterior tendon, which is common in athletes, resulting from an eversion injury causing disturbance or tears to the anterior and mid parts of the deltoid ligament when hyperpronation (eversion) occurs in plantarflexion or while the foot is flat on the ground respectively (O'Loughlin et al., 2009). However, medial ankle instability can occur and not be combined with dysfunction of the tibialis posterior tendon which may become affected after deltoid injury due to overloading and straining eventually leading to it being ruptured (Hintermann et al., 2004). On the other hand, deltoid insufficiency may result from attenuation and stretching of the ligament due to insufficiency in the tibialis posterior tendon (Deland et al., 2004). In addition, an osteochondral lesion of the talus may result in medial ankle pain and sprain (O'Loughlin et al., 2009). MRI showed isolated injury of the deltoid without other pathologies in 3 of 36 patients; the disturbance of the injured superficial and deep deltoid was found to be at the proximal and distal attachments respectively.

During fixation of a sustentaculum tali fracture, surgeons may need to split the deltoid insertion at the sustentaculum tali in order to provide better visualisation, as well as to reduce damage to the deltoid complex (Browner et al., 2015). LCL injuries were seen in 77% of cases of medial ankle instability, suggesting that deltoid injury may cause repetitive talar rotator shift resulting in LCL overuse. However, it is possible that the LCL already had an injury causing instability which then overloads the anterior part of the deltoid ligament. Persistent discomfort after LCL reconstruction may support this theory as medial ankle sprains may play a role (Hintermann et al., 2004).

2.8.3 Ankle instability

Ten to thirty percent of patients with lateral collateral injuries develop chronic lateral ankle instability (Peters et al., 1991), with disturbance to the ATFL and anterior and lateral capsule of the ankle joint being the main causes of chronic ankle instability (Sefton et al., 1979). In addition, chronic ankle instability results from functional instability (Hertel, 2000), loss of proprioception and weakness of the fibularis muscles (Willems et al., 2002). The loss of proprioception in patients with ankle instability agrees with Konradsen (2002) and Konradsen and Ravn (1990). Chronic ankle instability symptoms include chronic pain, repeated ankle sprains and a sensation of the foot giving away (Bortzman and Manske, 2011). Moreover, functional limitation and articular degenerative changes may occur from chronic ankle instability (Bortzman and Manske, 2011).

Patients with chronic instability may present either with functional instability that involves slowness in balancing or with mechanical instability that involves extreme ROM: it is possible to have both instabilities (O'Loughlin et al., 2009). Functional instability results in a deficiency in balance, sense of joint position, delayed reaction by the fibularis muscles, slowness of reaction of the fibular and sural nerves, weakness of the fibularis muscles and a decrease in dorsiflexion ROM (Hertel, 2000), while mechanical instability may occur due to disruption in ligamentous support leading to extreme ROM (Coughlin et al., 2014). Lateral chronic ankle instability results in abnormal varus and anterior and internal rotation of the talus (Sefton et al., 1979), as well as functional instability (Freeman, 1965). Balance deficiency has been reported in patients with chronic ankle instability (Brown and Mynark, 2007). Olmsted et al. (2002) reported a decrease in the reach point in patients with chronic ankle stability when standing on the injured foot and reaching with the normal foot in a different direction when compared to standing on the non-injured foot.

Medial ankle instability is not well explained in the literature (Ferran et al., 2009). However, patients with medial ankle instability present with a ‘giving way’ feeling of the ankle, pain on the medial aspect of the ankle, eversion (pronation deformity) and hindfoot abduction (Hintermann et al., 2004). Medial ankle degenerative changes and arthritis have also been reported in many patients with long standing lateral instability due to the medial loading on the ankle (Harrington, 1979). Unexplained instability or ’giving way’ of the ankle in some patients who underwent surgical intervention may be due to the deltoid ligament being compromised: this is not usually considered clinically (Hintermann, 2003).

2.8.4 Diagnosis

2.8.4.1 Physical Examination

A history should be taken from the patient including questions about previous injuries to ligaments of the ankle, the mechanism of injury and the sound heard during the injury, when the swelling occurs, previous medical history, the ability to bear weight and the emergency treatment received (Adams et al., 2013). Acute ankle sprains can be disregarded by the accident and emergency doctors, especially if no fracture exists; therefore, describing the mechanism of injury is important in the early diagnosis of the injury (Browner et al., 2015). This is accompanied by the difficulty of applying the physical examination technique to an acute sprain (Browner et al., 2015; Adams et al., 2013) when there is pain and swelling, especially in the acute phases which is when MRI is preferable in identifying the injury (Adams et al., 2013). Physical examination includes observation of tenderness and haemorrhage, the ankle bones and their ligaments, the neurovasculature, muscles crossing the ankle joint, the ankle ligaments, the base of 5th metatarsal, range of motion, instability tests such as the talar tilt and side to side tests (Adams et al., 2013) and the anterior drawer test (Figure 2.47) (Balduini et al., 1987). Moreover, in the diagnosis of an ankle sprain fractures of the distal fibula and base of the 5th metatarsal should be considered (Ferri, 2016).

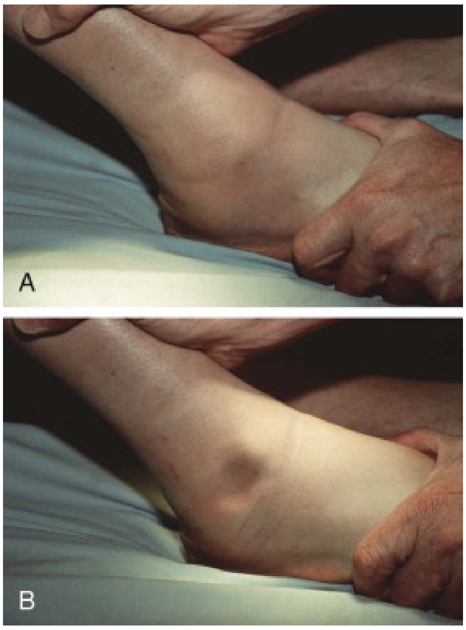

Figure 2.47 Positive anterior drawer test (Coughlin et al., 2014).

Lateral ankle sprains can be classified by degree (Ferri, 2016; Adams et al., 2013): grade I results in minor swelling due to microscopic tears rather than macroscopic tears; grade II feature minor to moderate swelling and some ankle instability resulting from a partial tear; grade III causes substantial swelling, discolouration, ankle instability and failure to bear weight (Adams et al., 2013). In addition, it is recommended that the deltoid ligament is also considered in cases of ankle instability when LCL injuries are examined (Ziai et al., 2015; Hintermann et al., 2004). Ross and Guskiewicz (2004) found that patients with ankle instability took longer to stabilise themselves after a single leg jump.

Tears of the deltoid ligament may present with a number of symptoms, including tenderness and swelling at the medial malleolar tip, while hypereversion may occur in complete tears (McConkey et al., 1991). According to Hinterman et al.

(2003), medial ankle instability can be classified into three types: type I, II and III lesions which result from proximal (72%), intermediate (9%) and distal (19%) tears or avulsion of the deltoid respectively. Types I and II also affect the TNL, TSL and spring ligament, while type III affects the TNL and spring ligament (Hintermann, 2003). An injury or rupture to the tibialis posterior tendon may produce symptoms similar to those of a deltoid injury; therefore, careful examination is important for differential diagnosis (McConkey et al., 1991).

2.8.4.2 Radiology

An inversion stress radiograph is taken to check the competence of the ATFL and CFL while the ankle is placed in plantarflexion and dorsiflexion respectively (Browner et al., 2015). However, there is disagreement regarding the importance of stress radiographs in diagnosing ankle instability.

Radiographic imaging of ankle sprains involves an AP view of the ankle to show the extent of talar tilt. Anaesthesia may be used if there is pain and the ankle is recommended to be placed in neutral, dorsiflexion or plantarflexion: this can be achieved manually or by using a jig (a device that is used to hold specimens). A varus tilt of 15° or more suggests a high possibility of complete disturbance of the ATFL which in many cases is accompanied by the CFL: a CFL tear may be shown more accurately when tilt is examined in neutral or slight dorsiflexion (Figure 2.48). In addition, the anterior drawer test (Figure 2.49) using stress radiographs may be performed manually or by using a jig: when there is 5 mm or more anterior translation of the talus it is indicative that the ATFL is torn (Coughlin et al., 2014).

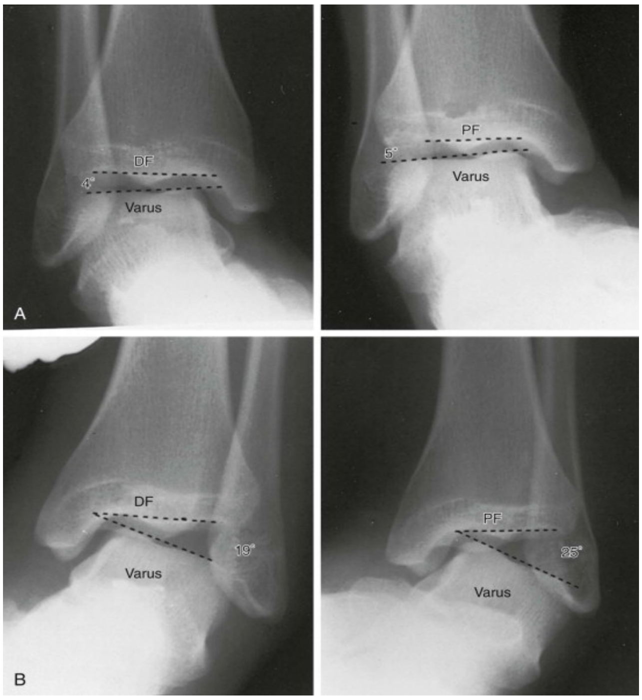

Figure 2.48 Examining talar tilt using radiographs: A, Normal tilt; B, abnormal tilt; DF, dorsiflexion, PF, plantarflexion (Coughlin et al., 2014).

Anatomical variations of the deltoid ligament may lead to misdiagnosis of injuries to the ligament; however, with advances in arthroscopy and radiological imaging deltoid injuries are becoming more readily identified (Savage-Elliott et al., 2013). Stress radiographs do not show medial ankle instability in all cases (Hintermann et al., 2004).However, van den Bekerom et al. (2009) consider that external rotation stress radiographs are an important diagnostic tool for determining deltoid incompetence. Koval et al. (2007) reported that MRI of patients with a positive stress test after fracture of the lateral malleolus showed partial (90%) and complete (10%) tears of the deltoid ligament. In addition, Jeong et al. (2014) demonstrated that MRI is able to visualise deltoid injuries which was found to be commonly complex and accomapanied with other ankle pathologies except in 8.3% of 36 ankles which had isolated deltoid injury. The rarity of isolated deltoid injury may be caused by confusing the injury with other conditions (Leith et al., 1997). McConkey et al. (1991) indicated that stress radiographs may help in better showing the instability, while MRI may help in locating the injury.

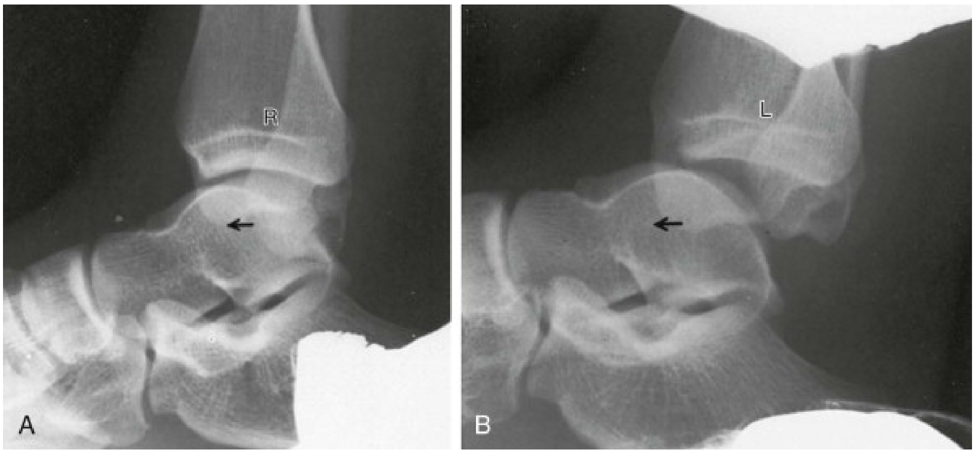

Figure 2.49 Anterior drawer test using stress radiograph showing anterior displacement of the talus (B) compared to the other normal side (A) (Coughlin et al., 2014).

MRI and ultrasound have been routinely used to diagnose acute lateral ankle injuries in athletes (van den Bekerom et al., 2013), providing accurate results in diagnosing injured lateral ankle ligaments (Ahmad et al., 1998). In an MRI study the accuracy of showing grades II and III ankle sprains was 25% and 100% respectively (Frey et al., 1996). MRI (Figure 2.50) is able to visualise deltoid injury (McConkey et al., 1991), with best visualisation of the ATFL, PTFL deep deltoid and TNL being observed when using axial MRI of the ankle (Figure 2.51A), while the PTTL, TCL, CFL and PTTL can be visualised using coronal views (Figure 2.51B) (Muhle et al., 1999).

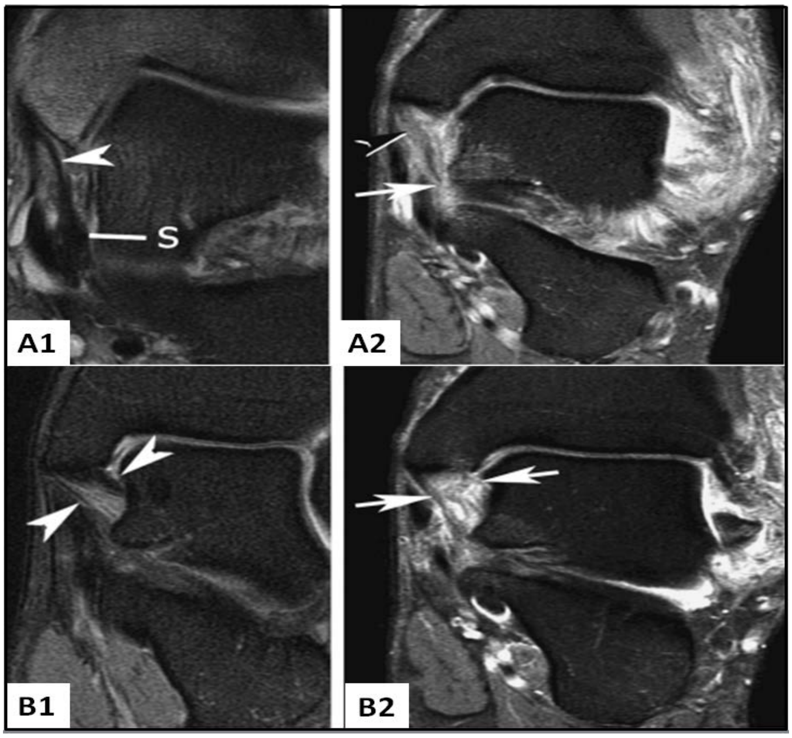

Figure 2.50 Coronal T2 MRI showing the difference between a normal superficial deltoid (A1) and an injured superficial deltoid (A2): proximal (arrow heads) parts of the ligament look different while the distal (white arrow) part is disrupted; in addition differences in the deep deltoid (arrowheads) in a normal (B1) and an injured deep deltoid (white arrows) in injured ankle (B2) are shown (modified from Koval et al., 2007).

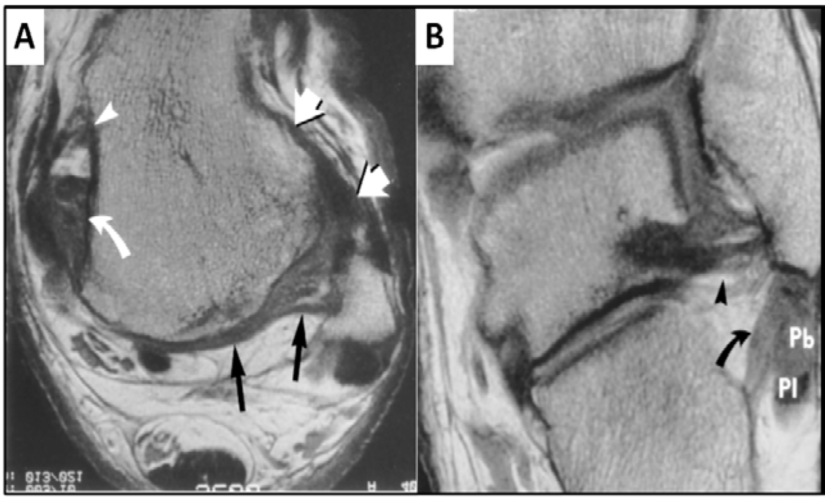

Figure 2.51 MRI axial imaging showing the anterior talofibular ligament (straight white arrows), the posterior talofibular ligament (PTFL) (black arrows), the anterior tibiotalar ligament (arrowhead) and the posterior tibiotalar ligament (curved arrow); B, MRI coronal imaging showing the calcaneofibuar ligament (arrow) and the PTFL (arrowhead) (modified from Muhle et al., 1999).

Ultrasound has been used in the accurate diagnosis of deltoid injuries (Figure 2.52) (Henari et al., 2011). The ankle ligaments, as well as injuries and sprains to them, can be easily seen in ultrasound (Morvan et al., 2001): stretching of the ligaments helps visualisation (Peetrons et al., 2004). Good results using arthroscopy in diagnosing and defining injuries to the deltoid ligament have been reported (Hintermann et al., 2004), with good diagnostic detail in 85% of ankle ligament tears (Ala-Ketola et al., 1977). Hintermann et al. (2004), using arthroscopy, showed medial instability in all patients studied with 69% requiring surgical intervention: in addition, patients also had an LCL injury (77%), tibialis posterior tendon elongation (12%), degeneration (10%) and spring ligament injury (21%) which needed repair. Therefore, the important details and abnormalities shown by arthroscopy must be appreciated before surgical reconstruction of the ankle ligaments is undertaken (Maffulli and Ferran, 2008; Hintermann et al., 2002).

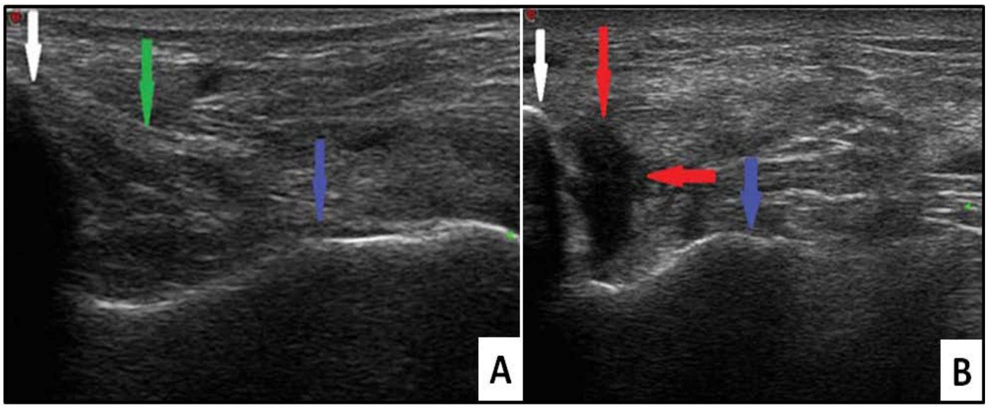

Figure 2.52 Ultrasonography showing intact (A) and disrupted (B) deltoid ligaments: white arrow, medial malleolus of the tibia; blue arrow, talus; green arrow, intact deltoid; red arrows, injured deltoid (modified from Henari et al., 2011).

2.8.5 Treatment

Early treatment of chronic ankle instability may help in preventing or decelerating degenerative changes of the articular surfaces that lead to osteoarthritis (Bortzman and Manske, 2011): misdiagnosing or mistreating lateral ankle instability can lead to disability (Ferran et al., 2009). However, there is disagreement regarding the most appropriate approach to treat ankle sprains in competitive athletes (Coughlin et al., 2014): treatment of ankle ligament injuries and instability is divided into conservative and surgical treatment.

2.8.5.1 Conservative (Non-Surgical) Treatment

Non-surgical treatment includes rest, applying ice, compression, elevation, exercise, pain medication, immobilization, using orthoses (Ferri, 2016) and rehabilitation (Hale et al., 2007): most ankle sprains can be controlled by conservative methods (Bortzman and Manske, 2011). Surgical reconstruction is not commonly undertaken for ankle sprains as non-surgical treatments are reported to be as satisfactory as surgical treatment; however, if the symptoms of lateral ankle instability continue then reconstruction can be recommended (Ferri, 2016).

It has been suggested that ankles with a grade III sprain can be immobilised with the ankle between 5 and 15° dorsiflexion to help decrease anterior displacement of the talus and bring the proximal and distal ends of the ATFL closer to each other, which may help in the healing process and provide stability of the ankle (Smith and Reischl, 1988). Woodman et al. (2013) treated a case with PTFL sprain using the conservative Mulligan manipulation technique, which involves mobilisation with movement as the fibula was repetitively moved anteriorly following the application of the tape. Good results were reported, although the patient had a mild feeling of instability. The patient had excellent improvement after one year: the theory behind this technique is that there was faulty positioning of the fibula that needed to be mobilised and taped in an anterior position. Deltoid injuries are usually treated conservatively giving it a chance to heal (Savage-Elliott et al., 2013). Non-surgical treatment of a deltoid injury is recommended for partial tears, while surgical intervention is recommended in patients with complete tears (Koval et al., 2007).

2.8.5.1.1 Rehabilitation

Acute ankle sprains can be managed using splints or taping for a few days with the ankle stabilised in neutral to prevent further ligament injury, especially in plantarflexion and inversion (Bortzman and Manske, 2011). In addition, ankle sprain rehabilitation aims to prevent further injury, manage the pain and swelling, strengthen muscles and provide proprioception training (Bortzman and Manske, 2011; Balduini et al., 1987), coordination (Konradsen, 2002) and functional training (Bortzman and Manske, 2011). Moreover, to improve ankle stability strengthening of the fibularis muscles is required (Willems et al., 2002) as resistance training of the ankle has shown improvements in balance in individuals with chronic ankle instability (Han et al., 2009).

Surgical reconstruction is not recommended unless there is a restricting pain or instability (Canale et al., 2016; Browner et al., 2015). Comprehensive rehabilitation that includes postural control and function of the lower limb has shown improvement in the functional limitations, although the mechanism of the improvement is not understood (Hale et al., 2007). Therefore, rehabilitation of an ankle sprain shows better results (Webster and Gribble, 2010) compared to immobilisation (Kerkhoffs et al., 2001). Malliaropoulos et al. (2009) found that only 17.8% of athletes followed for 2 years who underwent rehabilitation rather than surgery, had a repeated ankle sprain with higher risk for those with grades I and II ankle sprain compared to grade III.

2.8.5.2 Surgical Intervention Treatment

According to Peters et al. (1991) the majority of reports emphasise surgical reconstruction to treat chronic lateral ankle stability. However, according to previous studies surgical intervention may be recommended in cases such as repeated ankle sprains and preferably for younger patients and those physically more active (Korkala et al., 1987). In addition, a severe grade III ankle sprain is treated conservatively and surgical reconstruction done if instability occurs later: late reconstruction shows as good results as early repair (Cass et al., 1985). Surgical reconstruction of acute lateral ankle injuries is only recommended for high demand athletes or patients who do not improve with conservative treatment (Maffulli and Ferran, 2008). Ankle arthroscopy, used in diagnosing and treating ankle sprains, can be considered in patients that show no improvement with non-surgical treatment (Ogilvie-Harris et al., 1997).

There are more than 50 surgical approaches to reconstruct the ankle ligaments, suggesting that complete success and satisfaction of each procedure has not been accomplished (Becker et al., 1995; as cited by Bohnsack et al., 2002).

2.8.6 Surgical Treatment of the Ankle Injured Lateral Collateral Ligaments

Surgical release of the posterior soft tissues of the ankle in clubfoot and talar inversion deformity may involve releasing the long posterior fibres of the PTFL (Courvoisier et al., 2008). Surgery to reconstruct the LCL (ATFL and CFL) is divided into two categories: anatomical (Broström) and non-anatomical (reconstructive tenodesis) (Baumhauer and O'Brien, 2002). Furthermore, the anatomical approaches are divided into anatomical repair by ligamentous shortening and free tendon graft anatomical reconstruction (Jung et al., 2012; Ferran et al., 2009). However, these different surgical approaches lack a strong level I evidence base (evidence that was obtained from a randomised controlled trial (DeVries and Berlet, 2010)) that helps surgeons to decide on the optimal approach (Kennedy et al., 2012).

Jerosch et al. (2005) removed the skin and fascia of the lateral aspect of the ankle in a Thiel embalmed cadaver, then using coloured canuula that could be removed after marking, 33 orthopaedic surgeons experienced in ankle and foot surgery were asked to mark and define the distal attachment (insertion) of the ATFL and CFL that conformed to their surgical protocols and experiences: photographs were taken to document the variations. Dissection to the region was then undertaken to reveal the distal attachment of the ligaments and to compare it with the surgeons’ markings. No surgeon accurately defined the

ATFL or CFL distal attachment: the ATFL distal attachment was identified 15 ± 6 mm from the actual point, while CFL was determined 13 ± 9 mm from the distal attachment. In addition, three participants defined the ATFL distal attachment as being superior to the lateral malleolus, while two participants located the CFL distal attachment anterior to the lateral malleolus. In general, 79% defined all distal attachment more superiorly than it actually was (Jerosch et al., 2005).

2.8.6.1 Non-Anatomical Reconstruction (Reconstructive Tenodesis)

There are a number of non-anatomical approaches to correct lateral ankle instability and reconstruct injured ATFL and CFL: these include the Evans, the Chrisman-Snook and the Watson-Jones approaches (Buerer et al., 2013).

The Evans procedure (Figure 2.53) harvests half or the entire tendon of fibularis brevis proximally, while the distal insertion to the base of the 5th metatarsal is maintained. The free part of the tendon is inserted through a hole in the anterior fibula that ends posteriorly and is then sutured to itself and fixed (Baumhauer and O'Brien, 2002). Karlsson et al. (1988b) followed 42 patients who had LCL correction using the Evans procedure between 10 and 17 years: only 50% were satisfied, 10 patients had good initial results but stability deteriorated; 6 cases were able to participate in active sport, while there was limitation in inversion in 8 cases. Many later developed lateral instability, especially talar anterior displacement.

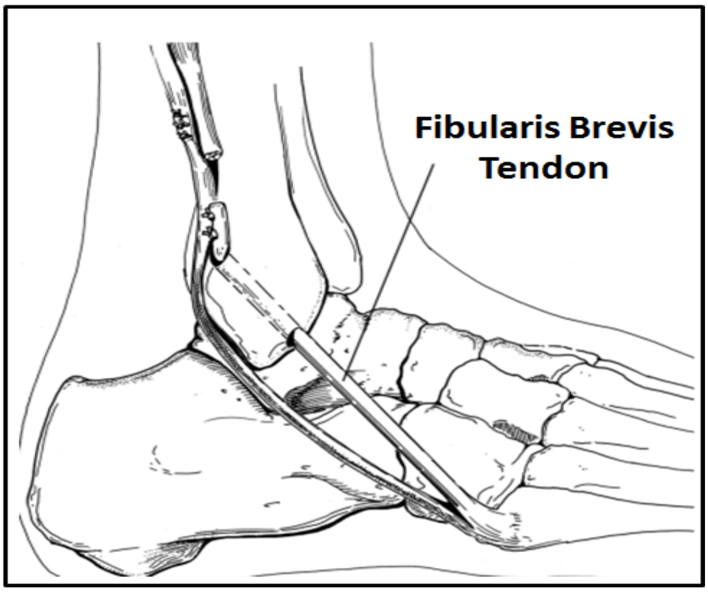

Figure 2.53 Evans Procedure (modified from Baumhauer and O'Brien, 2002).

The Chrisman-Snook procedure (Figure 2.54) splits the tendon of fibularis brevis proximally keeping the distal insertion to the base of the 5th metatarsal intact. The free limb of the tendon is inserted from anterior to posterior through the fibula and through a posterior to anterior hole in the calcaneus: it may be then suture it to itself or extended and sutured on itself at the location of the ATFL (Baumhauer and O'Brien, 2002). Snook et al. (1985) followed 48 cases who received the Chrisman-Snook procedure for lateral ankle instability: there were excellent results in 38, good in 7, fair in 2 and only 1 poor result. Patients who had severe injuries had fair and poor results, with those with fair results showing improvement but not regaining complete stability. The one patient with a poor result had generalised laxity of the ligaments (Snook et al., 1985).

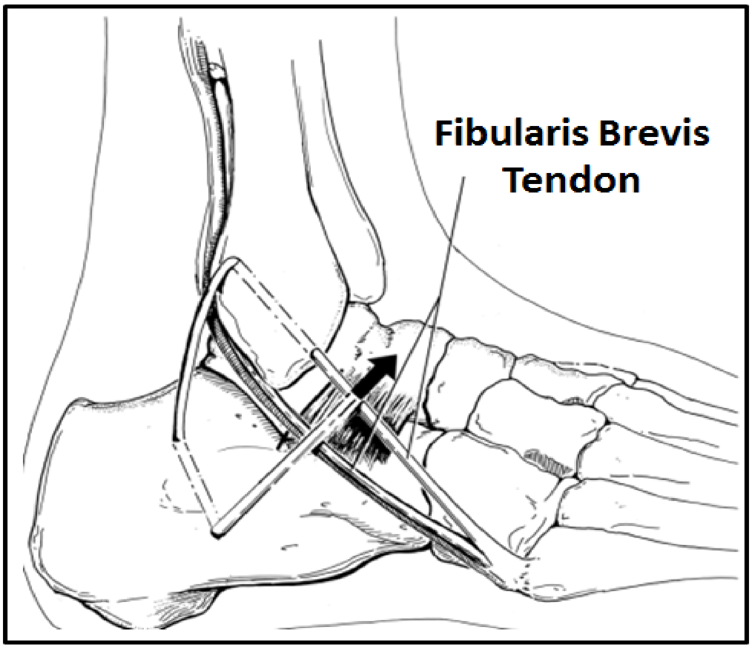

Figure 2.54 Chrisman-Snook Procedure (modified from Baumhauer and O'Brien, 2002).

The modified Watson-Jones approach (Figure 2.55) harvests the tendon of fibularis brevis: two holes are made with the first directed obliquely through the fibula in anteroposterior direction 2.5 cm superior to the lateral malleolar tip, and the second drilled in the talar neck directed superoinferiorly anterior to the ATFL. The free limb of the harvested tendon is inserted through the hole in the fibula from posterior to anterior and is then inserted through the hole in the talus from inferior to superior. The tendon is then moved posteroinferiorly behind the fibula and sutured to itself and as well as to the periosteum of the fibula (Canale and Beaty, 2013; Richardson, 2001). This approach is recommended for obese patients, those with ankle and subtalar instability, high risk injuries for athletes, patients who have had a previous failed anatomical procedure or patients with a connective tissue disorder (Richardson, 2001).

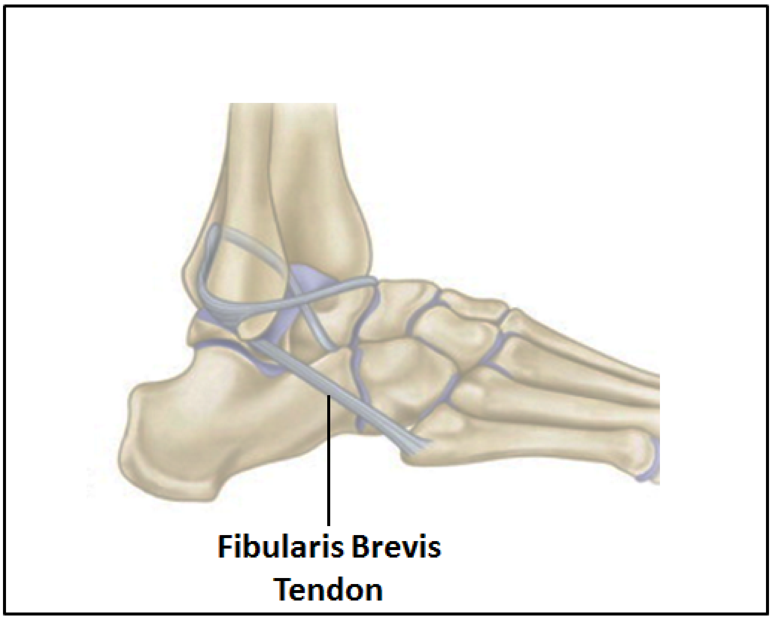

Figure 2.55 Modified Watson-Jones Procedure (modified from Canale and Beaty, 2013).

Using the tendon of plantaris as a graft in reconstructing the lateral ankle ligament has shown good results without jeopardising fibularis brevis, which resists inversion (Anderson, 1985). However, due to anatomical variation between individuals Wehbé (1992) reported that the plantaris tendon was absent in 19% of lower limbs examined. In addition, non-anatomical reconstruction using a semitendinosus allograft (Figure 2.56) was used by Ventura et al. (2014), who reported good results regarding stability, although there was restriction of subtalar motion (Figure 2.56).

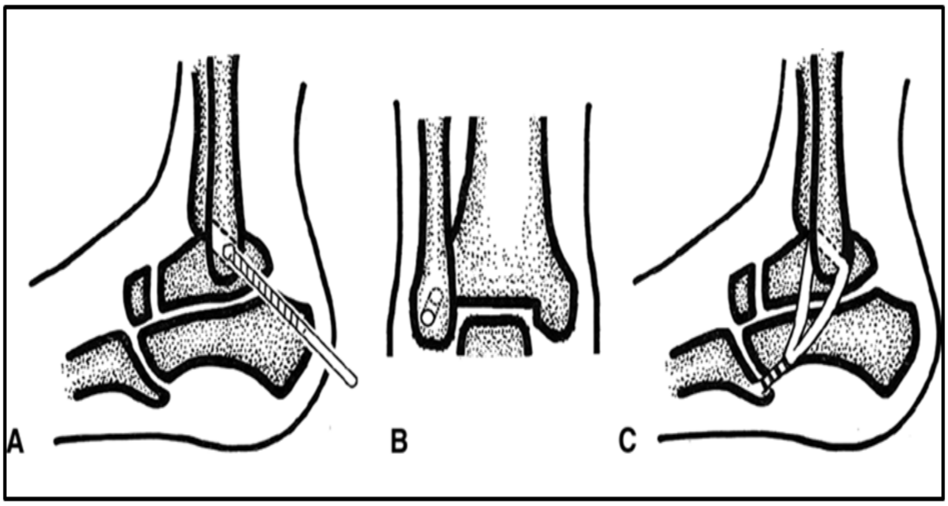

Figure 2.56 Non-anatomical reconstruction of the anterior talofibular and calcaneofibular ligaments using a semitendinosus allograft: A, Drilling tunnel in the fibula; B, the lateral and medial holes of the fibular tunnel; C, the allograft being fixed through the fibula and stabilised into the 5th metatarsal (Ventura et al., 2014).

The Evans procedure has been reported to result in an increased anterior displacement, internal rotation and talar tilt, while the Chrisman-Snook procedure increases anterior displacement and internal rotations; talar tilt is reported in the Watson-Jones approach: all three approaches are reported to restrict subtalar movement (Colville et al., 1992). Therefore, surgeons need to check subtalar instability and evaluate if the surgical approach requires modification (Gillespie and Boucher, 1971). Correcting an injured ATFL and CFL using non-anatomical procedures may produce good results; however it has been reported that patients often develop ankle instability later (Buerer et al., 2013). In addition, decreases in ankle and subtalar ROM (Baumhauer and O'Brien, 2002; Colville, 1998) may be affected according to the placement of grafts (Colville, 1998). There is also a risk of injuring cutaneous nerves (intermediate dorsal cutaneous nerve) and jeopardising the function of fibularis brevis (Colville, 1998), although both Pierre et al. (1984) and Gillespie and Boucher (1971) indicate that eversion strength is not significantly affected.

2.8.6.2 Anatomical Repair (Modified Broström Procedure)

The anatomical Broström procedure is generally recommended (Browner et al., 2015), especially in patients with moderate to severe instability who respond well to the modified Broström procedure having fewer complications (Canale et al., 2016). The Gould modification procedure is the same as Broström, but involves the extensor retinaculum (Nelson and Blauvelt, 2015).

The incision for the modified Broström procedure is alongside the inferior aspect of the lateral malleolus; the foot is kept everted. Repair to the ATFL and CFL (Figure 2.57) is performed at the point of the tear; however, when the CFL tear is at the calcaneus it becomes difficult to repair, then the extensor retinaculum is stabilised to the distal fibula in order to limit inversion. Patients are not allowed any movement for up to 6 weeks after surgery, keeping the foot in neutral by placing it in a cast for 4 weeks and then a splint for 2 to 4 weeks. Patients then have to strengthen the fibularis muscles, returning to normal activities, including sport, within 8 to 12 weeks (Canale et al., 2016). Broström (1966) used a flap from the LTCL to repair the ATFL in adverse conditions, which showed similar results. It has been reported that reconstructing both the ATFL and CFL produces better results compared to isolated reconstruction of the ATFL (Karlsson et al., 1988a). Patients who do not achieve good results with anatomical repair usually have other issues, such as ligament insufficiency, previous surgery or generalized hypermobility (Karlsson et al., 1988a).

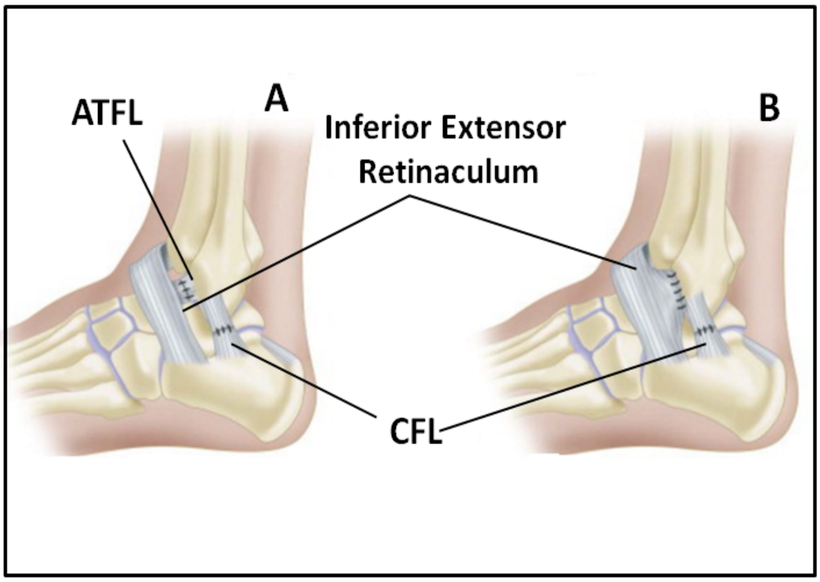

Figure 2.57 The modified Broström procedure to reconstruct the anterior talofibular (ATFL) and calcaneofibular (CFL) ligaments: A, anatomical repair of the ATFL and CFL at the midsubtance; B, mobilising the inferior part of the extensor retinaculum to the inferior aspect of the fibula (modified from Canale and Beaty, 2013).

The modified Broström procedure has received good reviews in a number of investigations (Buerer et al., 2013; Cho et al., 2013; Ahn et al., 2007; Bell et al., 2006; Hamilton et al., 1993; Karlsson et al., 1988a). In addition, Hamilton et al. (1993) recommend this procedure to resolve lateral ankle instability in dancers and athletes as it helps stabilise the ankle joint, regain full ROM and does not affect fibularis muscle function. In addition, Hennrikus et al. (1996) concluded that both the Broström and Chrisman-Snook procedures produce satisfactory stability in more than 80% of patients; however the Chrisman-Snook approach was found to have more complications.

Rehabilitation following the Broström procedure of lateral ankle instability includes stabilising the foot and preventing plantarflexion and inversion using braces and splints for up to 6- 8 weeks, gradual ROM training from week 4, strengthening the fibularis muscles from week 4, proprioception and balance training starting in week 6 and then between weeks 8 – 12 the patient can return to normal activities as long as there is no limitation or weakness (Bortzman and Manske, 2011).

2.8.6.3 Anatomical Reconstruction using grafts

Anatomical reconstruction of the ATFL and CFL should be performed when the condition of the ligaments is not suitable for repair (Maffulli and Ferran, 2008). Coughlin et al. (2004) performed anatomical reconstruction of the ATFL and CFL (Figure 2.58) using the gracilis tendon to avoid affecting the function of the fibularis muscles; patients were followed for an average of 23 months postoperatively. The ATFL proximal attachment was cut leaving a small amount of tissue for imbrication. Three tunnels were made one through the neck of the talus vertically exiting from the sinus tarsi; a second in the lateral surface of the calcaneus slightly inferior and posterior to the fibular longitudinal axis which is achieved by two horizontal holes 10 mm apart, then connected using an angle curette. The third tunnel hole is made vertically through the lateral malleolar tip and another connecting horizontally located anteriorly 20 mm superior to the lateral malleolar tip. The free end of the graft was passed through the calcaneal tunnel and sutured to itself as shown in Figure 2.58. It was then passed superiorly deep to the fibularis tendons and through the fibular tunnel from the tip to emerge anteriorly and then passed through the talar tunnel vertically exiting in the sinus tarsi and returned to be passed in the fibular tunnel anteriorly to exit through the malleolar tip passing distally, it was then sutured.

The reconstruction is done with the foot in neutral, with the CFL graft axis 10° posterior to the lateral malleolar tip while the axis of the ATFL graft is along the talar lateral axis. The postoperative protocol includes a cast for 8 weeks, physiotherapy and strengthening exercises. The results were satisfactory with no complaints being reported, except that 11% and 10.7% of patients had difficulty in walking on uneven ground and mild movement restrictions respectively. Coughlin et al. (2004) reported that patients returned to normal daily activities in 12 weeks and athletes returned to sport in 6.5 months. In addition, 14.36% sustained a sprain injury after surgery, but it did not cause ankle instability: 25% of patients had ligamentous laxity, among which only one had recurrent sprain (Coughlin et al., 2004).

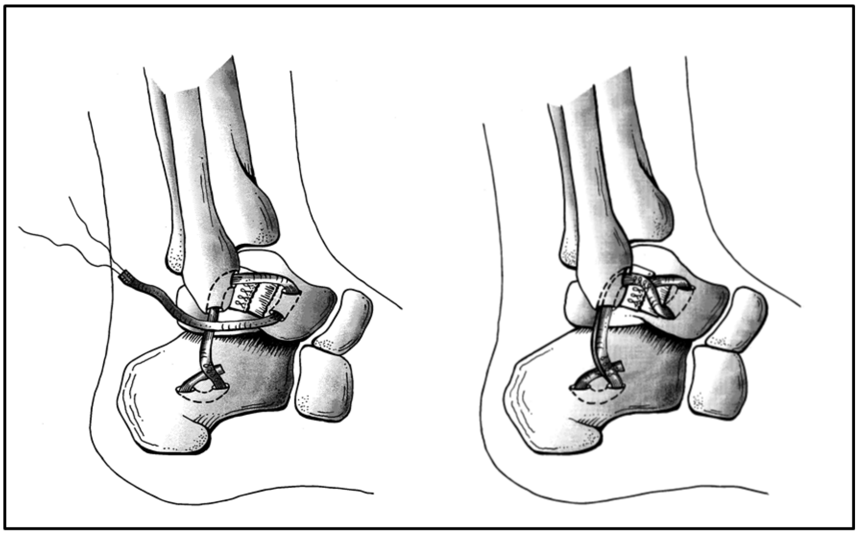

Figure 2.58 Coughlin et al. (2004) method of anatomically reconstructing of the anterior talofibular and calcaneofibular ligaments using an autologous gracilis graft.

Using the tendon of fibularis brevis is not recommended, especially in athletes, as it affects the biomechanics of the ankle joint and hindfoot (Ferran et al., 2009). Using a hamstring autograft to reconstruct the ATFL and CFL has been discussed by Paterson et al. (2000) and Jeys and Harris (2003). Paterson et al. (2000) used a semitendinosus graft (Figure 2.59A) to anatomically reconstruct the ATFL when anatomical repair was not possible: good results were reported on a short term follow up (average 24 months), but long term results were not reported.

In 2012, Hua et al. used a semitendinosus allograft (Figure 2.59B) to anatomically reconstruct the ATFL and CFL: two posterosuperior oblique tunnels were made in the fibula, one for the CFL and the other for the ATFL 7 and 13 mm superior to the lateral malleolar tip; another tunnel was made in the talus 18 mm superior to the subtalar joint; one last hole was created in the calcaneal tubercle on the lateral surface. The allograft then was passed through the talar tunnel and sutured with the ankle in neutral, checking plantarflexion ROM. Good results and a good ROM were reported. In the same year Jung et al. (2012) used a semitendinosus tendon allograft to anatomically reconstruct the ATFL and CFL (Figure 2.59C).

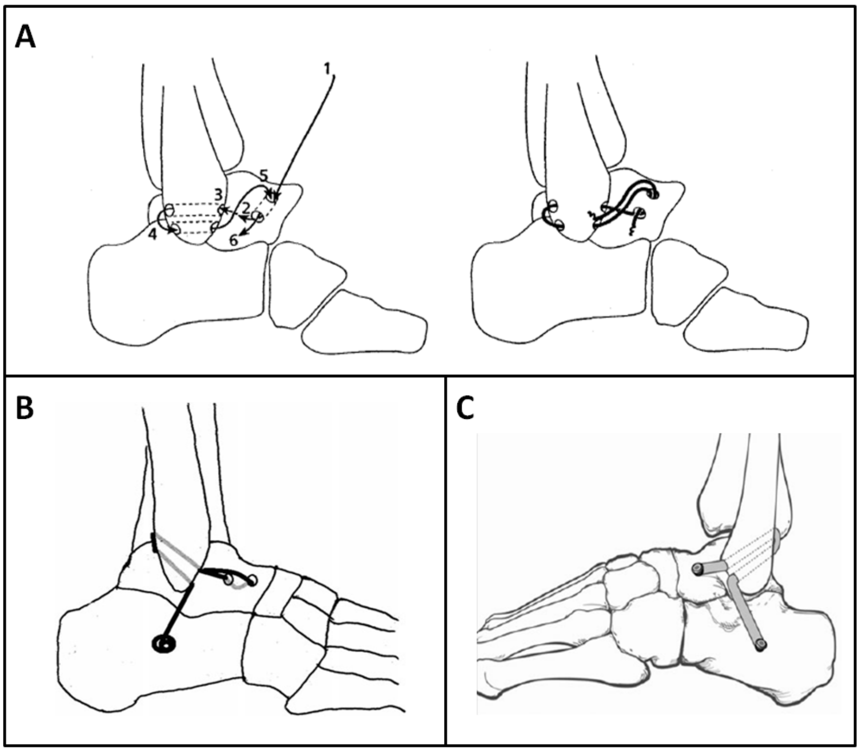

Figure 2.59 Anatomical reconstruction of anterior talofibular ligament using different grafts: A, Paterson et al. (2000) used a free semitendinosus tendon graft; B, Hua et al. (2012) and C, Jung et al. (2012) used a semitendinosus tendon allograft.

Ahn et al. (2011) used a new technique to anatomically reconstruct the ATFL and CFL using an autograft tendon of the long extensor muscle of the fourth toe. Two tunnels (Figure 2.60) were made in the lateral malleolus, with their inferior exits simulating the ATFL and CFL proximal attachments. Three small holes were created to fix the remnants of the ATFL and CFL. The autograft is inserted through the distal insertion of the ATFL remnant and fixed at this location; when the ATFL distal insertion was unstable the graft was fixed to the talus; the graft passed to be sutured to itself in the fibula after doubling the graft of ATFL and this can be done to the CFL as well.

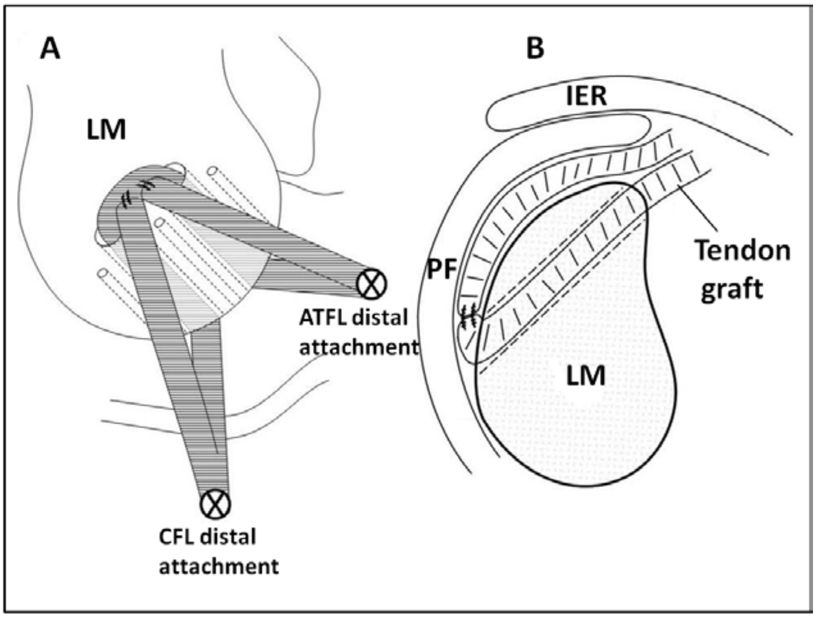

Figure 2.60 Ahn et al. (2011) used a tendon graft of the long extensor muscle of the fourth toe: A, the graft serves as a double graft for anterior talofibular (ATFL) and calcaneofibular (CFL) ligaments and fixed into two holes in the lateral malleolus (LM) proximally and into the ATFL and CFL insertions distally; B, cross section showing the final steps of the procedure of suturing and augmenting the periosteal flap (PF) and inferior extensor retinaculum (IER) (modified from Ahn et al., 2011).

Kennedy et al. (2012) proposed and used a new hybrid technique to anatomically reconstruct the ATFL using part of the fibularis longus tendon. The concept was to use both anatomical and non-anatomical reconstruction of the ATFL when repair is not possible. Surgery (Figure 2.61) was performed on 57 patients: 1/3rd of the width of the fibularis longus tendon was harvested and prepared as a graft, two holes were drilled in the proximal fibular (30 mm superior to the lateral malleolar tip) and distal talar attachment (not defined). Then, the graft was inserted into the holes with the ATFL remnant fixed to the graft to provide better support and preserve proprioceptive sensation for stability. As in other studies good results were reported and most patients returned to sport; however, 9% had functional instability resulting in not being able to return to sport (Kennedy et al., 2012).

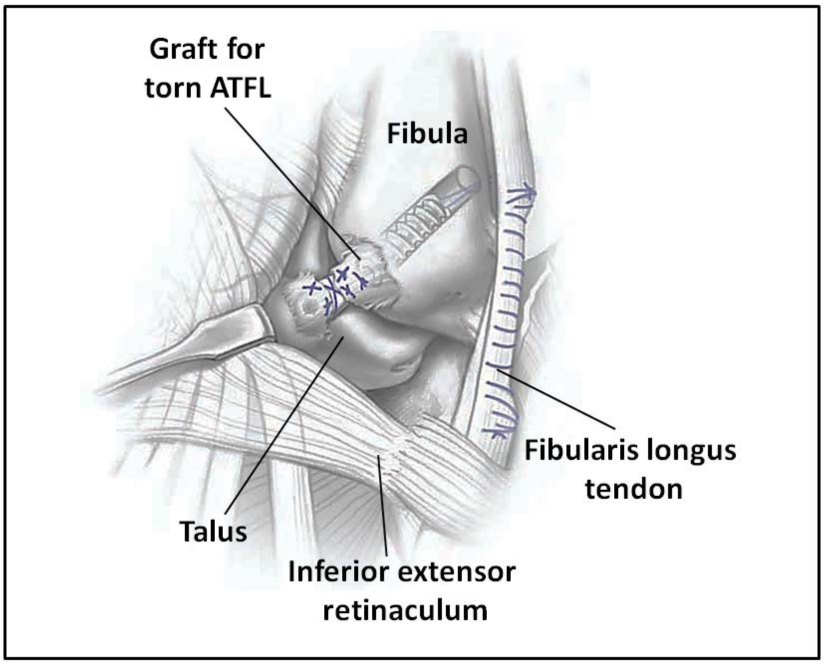

Figure 2.61 The Kennedy et al. (2012) hybrid approach to reconstructing the anterior talofibular ligament (ATFL).

Another approach with reported good results used periosteal flaps to reconstruct the ATFL and CFL (Rudert et al., 1997; Roy-Camille et al., 1986). As shown in Figure 2.62, Rudert et al. (1997) used two periosteal flaps taken from the distal fibula and inserted into two holes in the fibula simulating the ATFL and CFL proximal attachment sites (not defined): flaps were sutured and pulled toward the ATFL and CFL anatomical distal attachments. The flap that replaced the CFL passed deep to the fibularis tendons: two cortical bone grafts were taken from sites of the ATFL and CFL distal attachment to fix the ligament under them by stapling to them. According to the authors, there were good to excellent results in 81% of patients.

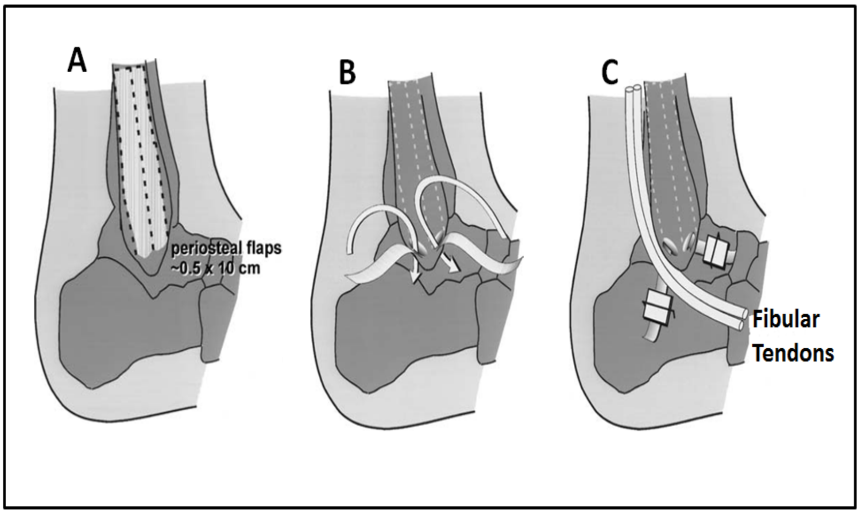

Figure 2.62 Using periosteal flap grafts to reconstruct the anterior talofibular (ATFL) and calcaneofibular (CFL) lgaments: A, periosteal flaps from the fibula; B, two periosteal flaps being dissected and two holes drilled in the fibula to simulate the ATFL and CFL proximal attachments; C, Fixing the ATFL and CFL distal parts using cortical bone blocks and a stapling technique (modified from Rudert et al., 1997).

Other anatomical approaches that have been introduced to reconstruct lateral ankle instability when the ligaments are not sufficient for repair have used different grafts, including the plantaris tendon (Pagenstert et al., 2006; Palladino et al., 1991; Anderson, 1985) providing a long graft (Pagenstert et al., 2006), a tibialis anterior tendon allograft (Ellis et al., 2011) and half of the fibularis longus tendon (Kim et al., 2014). These new anatomical reconstruction approaches provide a firm fixation for the tendon, especially in patients with insufficient ligaments that cannot be repaired. However, all investigations undertaken have only reported short term results: the long term outcomes are still unknown and require further investigation (Jung et al., 2012).

Bohnsack et al. (2002) studied the biomechanical stability of the different grafts used to reconstruct ankle instability. They indicated that grafts from fibularis longus, fibularis brevis, and a split calcaneal tendon had high tensile strength and ultimate load compared to the ATFL; therefore, they were considered to provide the greatest biomechanical stability. Moreover, the plantaris tendon had high tensile strength but low ultimate load. Periosteal flaps had inferior biomechanical characteristics compared to the tendon grafts; however, they were similar to that of the ATFL. Success of surgical procedures using periosteal flaps may be due to fibroblastic characters that help in providing function. However, a cast or arthrosis is essential in procedures that use periosteal flap grafts in order to give sufficient time for healing.

2.8.7 Surgical Treatment of Injured Ankle Medial Collateral Ligaments

Reconstruction of the deltoid has not been commonly discussed in the literature (Deland et al., 2004). Injury to the deltoid is surgically repaired or reconstructed when there is complex fracture or chronic instability (Savage-Elliott et al., 2013). However, repairing the deltoid ligament is not as satisfactory as repairing the ATFL and CFL; this may be because of the shortness of the deep deltoid fibres and the increased tension of the medial ankle structures (Canale and Beaty, 2013)

Stromsoe et al. (1995) suggested that a deltoid injury resulting from ankle fracture need not to be repaired. This is because surgical reduction of the lateral malleolus and reducing the medial joint space (between the medial malleolus and talus), may help in healing of the deltoid ligament without surgical intervention in fractured ankles (Sproule et al., 2004; Harper, 1988). In addition, the literature emphasises not reconstructing acute deltoid injuries (Savage-Elliott et al., 2013).

Hintermann et al. (2004) treated medial ankle instability by shortening the TNL and TSL and fixing them: when the LCL was also injured anatomical reconstruction was performed using a plantaris tendon graft when anatomical repair was not possible. In addition, calcaneal lengthening using a graft from the iliac crest was performed in cases when there was severe attenuation of the TNL, TSL and spring ligament as well as in severe eversion (pronation) deformity. The procedure results in widening the ankle mortise leading to correction of the valgus deformity; the postoperative protocol involves an appropriate rehabilitation programme and use of stabilising shoes for 6 weeks. Good results were obtained except in patients with bilateral or long valgus (pronation) deformities.

The Deland approach uses the fibularis longus tendon to reconstruct a failed deltoid ligament. Surgery is performed by transecting the fibularis longus tendon proximally and attaching the remaining part to fibularis brevis; the distal attachment of the transected tendon to the 1st metatarsal base is kept intact (Figure 2.63). The tendon is inserted in a horizontal tunnel through the talar neck, starting laterally and running plantardorsally exiting medially through the talar body. The graft is tensioned using screws following which it is passed through a tibial tunnel running from the medial malleolar tip through the intercollicular groove passing superolaterally 60° to exit from the lateral border where it is tensioned, secured and stapled (Canale and Beaty, 2013; Deland et al., 2004).

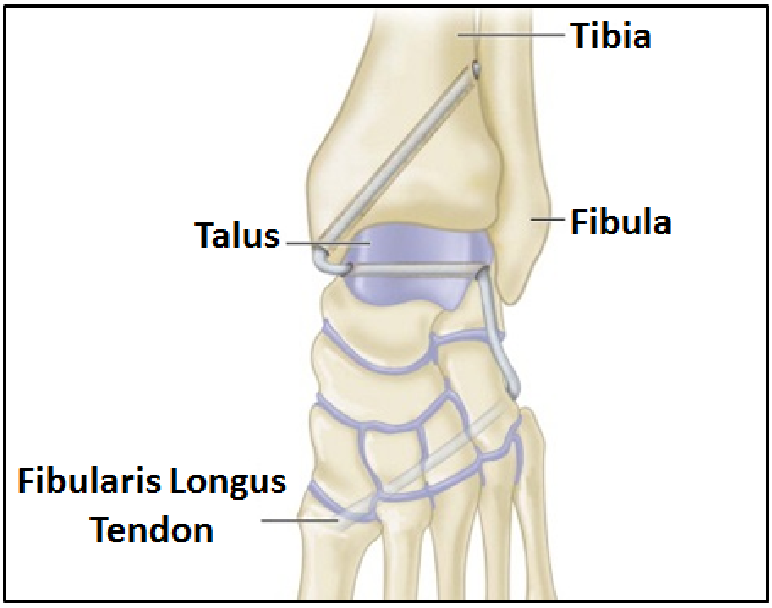

Figure 2.63 The Deland reconstruction procedure of the deltoid ligament (modified from Canale and Beaty, 2013).

Correcting valgus deformity helps in decreasing the risk of ankle arthrodesis or ankle replacement in some cases with advanced stage acquired flat foot deformity. Deland et al. (2004) used the Deland approach to reconstruct a failed deltoid ligament in patients with a valgus tilt deformity caused by stage IV adult acquired flatfoot (posterior tibial tendon insuffiency; PTTI). According to the authors good results were seen with good eversion strength, except in one patient in which the procedure was a failure; talar tilt was 9° although it decreased from that preoperatively (15°). No other ankle surgery was undertaken in the 3 year follow up, but there were complaints of mild lateral ankle pain. In addition, there were two cases with mild limitation in walking (Deland et al., 2004). Hintermann et al. (1999) corrected the deltoid ligament in similar cases of PTTI using either repair or reconstruction techniques. Ellis et al. (2010) also corrected valgus talar tilt deformity in patients with stage IV PTTI using the Deland surgical approach, which gave patients a better level of activity: none required joint replacement.

In 2011, Jeng et al. performed a new minimally invasive surgical technique to reconstruct the deltoid ligament in order to correct valgus deformity in patients with advanced stage IV acquired adult flat foot deformity using a hamstring tendon allograft. Tunnels through the tibia, talus and calcaneus were made (Figure 2.64). The tibial tunnel was drilled horizontally through the distal tibial physeal scar; the talar tunnel was drilled from medial to lateral, with the entrance located at the deltoid talar footprint and exited laterally at the junction between the talar body and neck; the calcaneal tunnel was drilled from the calcaneal sustentaculum tali medially exiting laterally 10 mm proximal to the calcaneal fibular tubercle. However, the talar and calcaneal tunnels may compromise the distal attachments of the ATFL and LTCL respectively. The non-split graft end was inserted and fixed into the tibial tunnel, while the other free ends were inserted and stabilised inside the talar and calcaneal tunnels as shown in Figure 2.64. The authors reported successful results in correcting the deformity in 62.5% of patients, but failure was demonstrated in the remaining 37.5%. They state that they created and used this new technique as the previous approaches were unsatisfactory (Jeng et al., 2011).

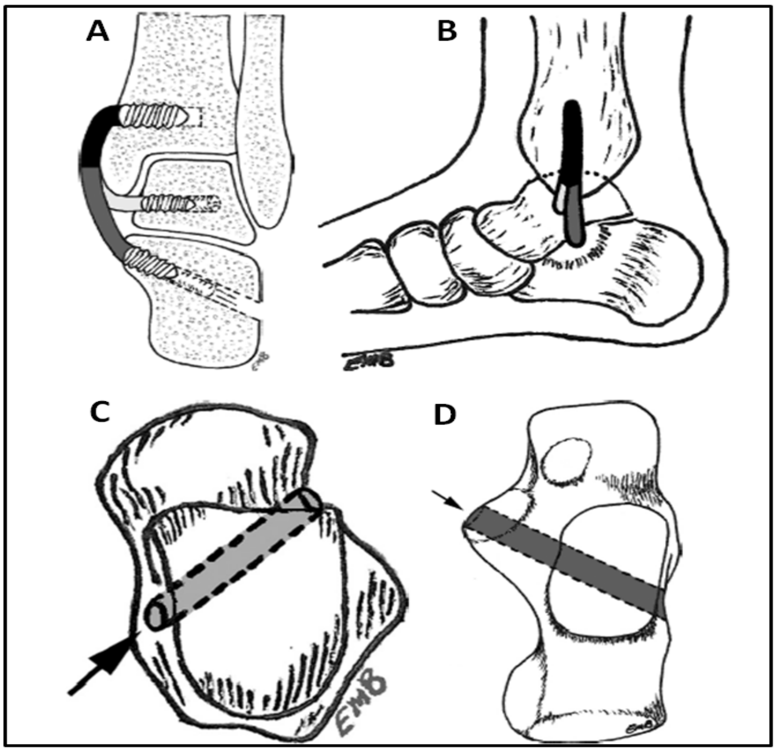

Figure 2.64 The Jeng et al. technique to reconstruct the deltoid ligament as part of treating acquired flatfoot deformity: A, coronal view of the used hamstring tendon allograft that inserted into tunnels in tibia, talus and calcaneus; B, posterior view of the ankle showing the reconstruction; C, tunnel through talus; D, tunnel through calcaneus; arrows indicate the entrance of the tunnel drilling (modified from Jeng et al., 2011).

The tendon of tibialis posterior should be investigated in surgical reconstruction of the deltoid ligament type II and III injuries; possible treatments that can be introduced include shortening, tensioning and repairing as well as removing accessory bones (Hintermann, 2003).

2.8.8 Preventive Methods

Injury prevention is appreciated among medical professionals who are involved in treating athletes (Beynnon et al., 2002). Ankle sprains may be prevented by balance training, strengthening the fibularis muscles and using braces and tapes, as well as perturbation training (Bortzman and Manske, 2011).

Balance training in patients with an ankle sprain reduces the risk of sustaining an ankle sprain in the future (McKeon and Hertel, 2008). Evidence shows that ankle braces and taping reduce the risk of a lateral ankle sprain in patients with an ankle sprain by 69% and 71%: there is no evidence of its effectiveness in non-injured ankles (Dizon and Reyes, 2010). However, braces provide no benefit in improving stability in patients with chronic ankle instability (Gribble et al., 2010; Hopper et al., 2009), although taping can help in restricting plantarflexion during activities that involve jumping and landing.

It has been reported that individuals with an ankle sprain that occurred in the last 6 to 12 months are at a higher risk of reinjuring the ankle during playing volleyball; therefore patients have been recommended to wear an ankle support during sporting activities (Bahr and Bahr, 1997). Footwear may impair the sensation of joint position and may be a risk factor in sustaining an ankle sprain (Robbins and Waked, 1998).There are good quality high top shoes with special lacing which have been used in basketball and have a role in guarding an instable ankle and preventing further injury (Petrov et al., 1988). However, this contradicts others who found no difference in using modified basketball shoes or lightweight military shoes in ankle sprain incidence rates (Milgrom et al., 1991)

Rigid and semi-rigid supports may not protect against sprains and may indeed cause injury due to restricting movement. If they do prevent ankle sprain this may result from the partial correction effect on the position of the foot caused by the footwear and so help increase the awareness of the position of the joint (Robbins and Waked, 1998). Feuerbach et al. (1994) agree as they reported an improvement in the sense of joint position with an ankle orthosis.

3 Material and Methods

3.1 Sample

Sixty-eight feet (34 right, 34 left) were studied from 36 formalin embalmed cadavers (64 bilateral, 4 unilateral) donated to the Centre for Anatomy and Human Identification (CAHID) at the University of Dundee under the Human Tissue (Scotland) Act 2006. The embalming method involved using the Dodge solution which consists of 8.9% formaldehyde; then a full strength phenol solution (> 90%) was added as 1/3 of 2.5 L bottle to 22.5 L of the solution (phenol = 3 – 4%). Blood was drained and 1 L of warm water and 1 L of metaflow product (pre-coinjection embalming chemical by Dodge) were perfused; then 15 – 25 L of the embalming solution was used depending on the body size. The population sample had an average age of 83.54 years (range: 62 to 98 years) and comprised 26 males and 42 females. The cause of death was known for each individual, with no cases of a history of injury or surgical repair to the ankle joint or to the lateral or medial collateral ligaments at the time of death.

3.2 Instruments and Equipment

- Dissection tools: dissection scissors, scalpels and blades, forceps.
- Camera: Nikon D80 DSLR (digital single-lens reflex) camera; 10.2 megapixels; country of manufacture: Thailand; with a lens 18 - 200 mm; country of manufacture: Japan.

- Electronic digital vernier caliper (Figure 3.1): Caliper (Toolzone 150 mm); country of manufacture: China.
- Plastic Protractor and measurement tape (3 m X 16 mm; brand: Draper).
- Plastic Goniometer (Figure 3.2) 360^0 clear 8 inch plastic goniometer (Brand 66FIT, Country of manufacture: China).
- Clamp: Stanley 183069 Multi Angle Hobby Vice 3 inch jaw opening

Figure 3.1 Electronic digital vernier caliper.

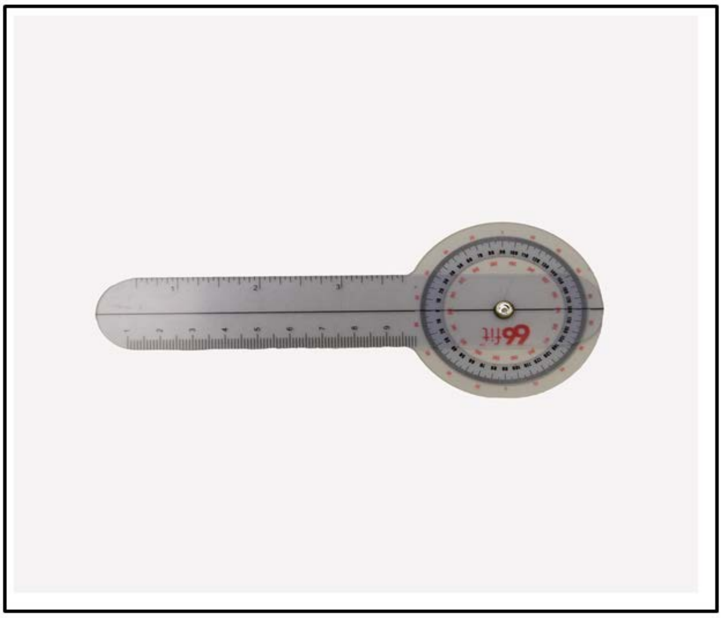

Figure 3.2 Plastic goniometer.

3.3 Preparation and Dissection

The feet were harvested with the lower third of the leg to preserve the ankle and subtalar joints and dissected on their anterior, posterior, lateral and medial aspects by removing the skin, fascia, superficial veins and cutaneous nerves. Following this a preliminary dissection was undertaken to expose and preserve the LCL and MCL for examination. Dissection of the anterior aspect of the ankle involved removing the inferior extensor retinaculum, the tendons of tibialis anterior, extensor digitorum longus, extensor hallucis longus and fibularis tertius, the anterior tibial and dorsalis pedis artery, the superficial and deep fibular nerves. The anterior talofibular ligament (ATFL), part of the calcaneofibular ligament (CFL) and a small part of the deltoid ligament were subsequently exposed for examination. The calcaneal tendon was removed posteriorly resulting in exposure of the posterior talofibular ligament (PTFL).

The medial aspect of the ankle was investigated by sectioning the flexor retinaculum and reflecting the tendons of tibialis posterior, flexor digitorum longus and flexor hallucis longus, as well as removing the posterior tibial artery, great saphenous vein, tibial nerve and the terminal branch of the saphenous nerve. Consequently, all the components of the medial collateral ligament (MCL; deltoid) were exposed prior to their investigation. In addition, the lateral aspect of the ankle was dissected by sectioning the tendons of fibularis longus and brevis, the small saphenous vein and sural nerve: this uncovered the CFL prior to examination.

To preserve as much of each ligament's fibres as possible, great care was taken during the dissection, with the fat and fascia between the different bands of the various ligaments removed with caution to avoid damaging the fibres of each ligament as much as possible.

3.4 Passive Range of Motion (PROM)

The passive range of motion (PROM) of dorsiflexion and plantarflexion of the ankle was determined using a plastic goniometer. The fulcrum of the goniometer was placed over the lateral malleolus, the stationary limb was positioned in line with the lateral surface of the fibula and the movable limb adjusted to become parallel to the 5th metatarsal (Figure 3.3) while the ankle was passively dorsiflexed or plantarflexed. The starting position was the neutral position in which the foot was at an angle of 90° to the leg.

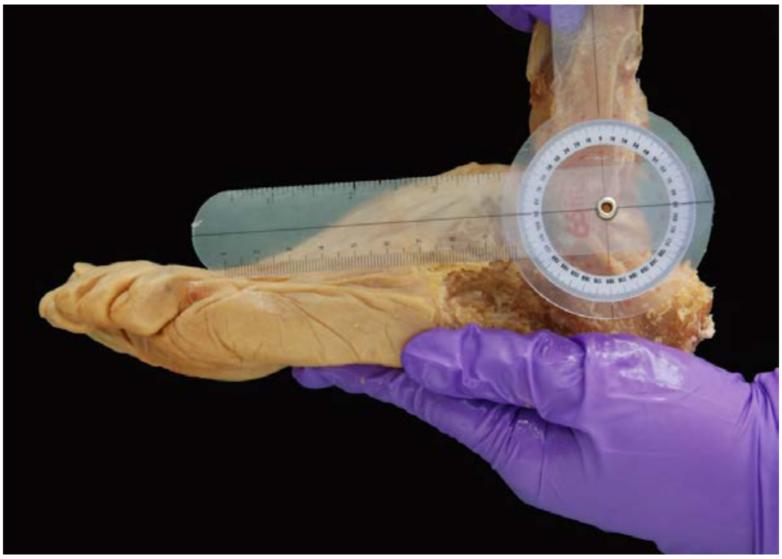

Figure 3.3 Starting position (neutral) for the measurement of the passive range of motion of the ankle dorsiflexion and plantarflexion.

The passive range of motion of inversion and eversion were measured in two different ways using the goniometer. In the first method (Figure 3.4) the goniometer fulcrum was positioned anterior to the ankle joint midway between the lateral and medial tibial malleoli, the stationary limb was placed on the shaft of the tibia, while the movable limb was positioned on the line from the ankle to the 2nd metatarsal and toe. The foot was then moved to maximum inversion or eversion with the movable limb measuring the PROM.

Figure 3.4 Measuring the passive range of motion of inversion and eversion.

Another method of measuring PROM during inversion and eversion was by measuring the range of isolated inversion or eversion without dorsiflexion or plantarflexion (Figure 3.5). Using a clamp, the foot was held with the posterior surface of the ankle superior (similar to a patient lying in a prone position). Then, the goniometer fulcrum was positioned on the posterior surface of the ankle midway between the lateral and medial malleoli, the stationary limb was placed parallel to the calcaneal tendon while the movable limb was placed on the same line of the stationary limb (angle between them 0°). Then the talus was palpated and stabilised while a passive movement was applied to rotate the calcaneus medially or laterally at the talocalcaneal joint; these methods of measuring the passive range of motion are similar to those used in clinical examination.

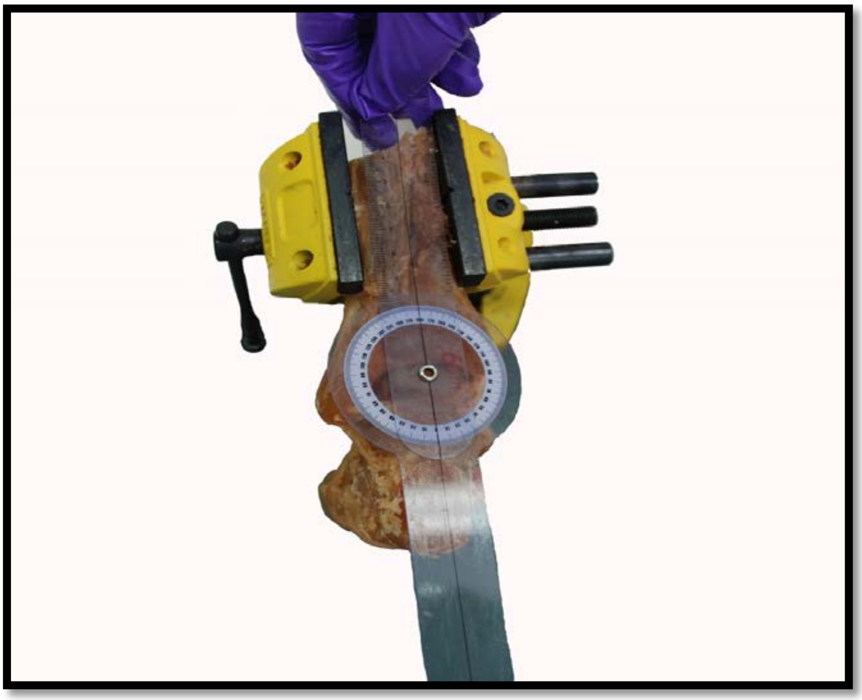

Figure 3.5 Second method of measuring the passive inversion/eversion range of motion.

3.5 Foot and 1st Metatarsal Length

The midpoint between the medial and lateral tubercles of the calcaneus was identified (Figure 3.6) in order to measure foot length, which was taken from this point to the tip of the 2nd toe. This measurement was taken because knowing foot length may help in determining the relationships between the foot length (size) and the various parameters measured. After taking all the data and measurements from the specimens, the 1st metatarsal was disarticulated then cleaned of surrounding tissues and fat. The disarticulated 1st metatarsal was placed into graph paper and two lines parallel to the extreme dorsal and proximal bony ends drawn (Figure 3.7): the distance between two lines was measured using a digital calliper.

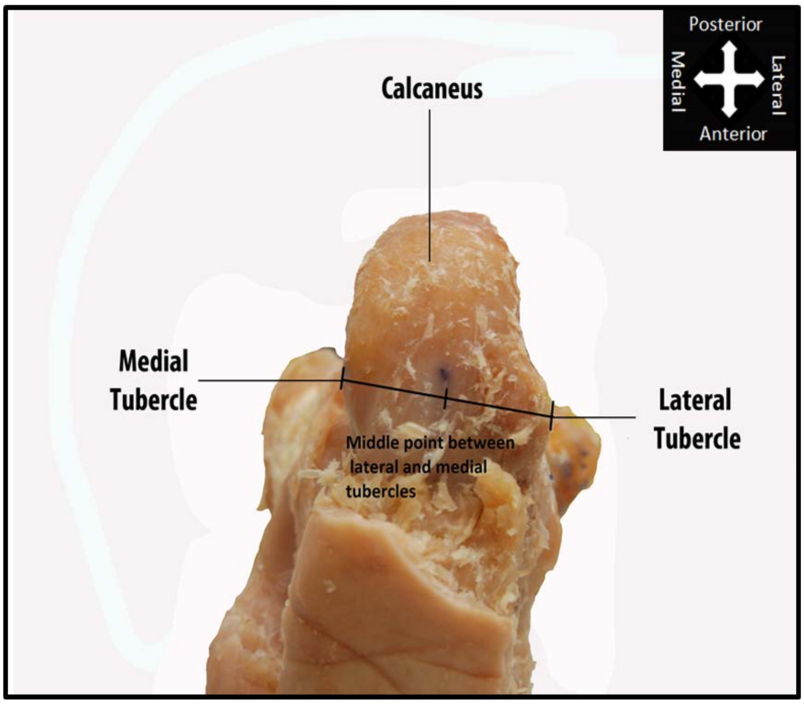

Figure 3.6 Midpoint between the lateral and medial tubercles of the calcaneus.

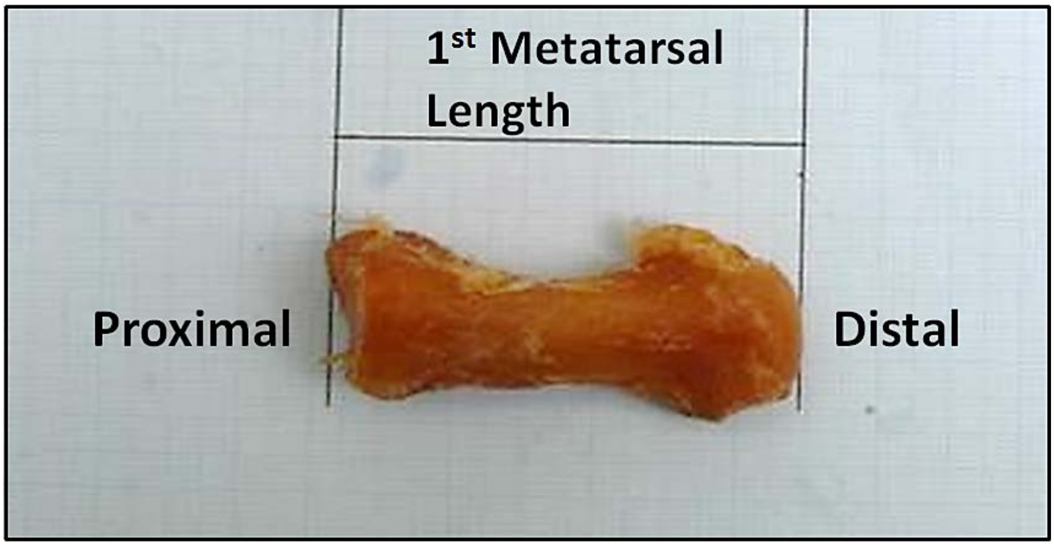

Figure 3.7 Measurement of the 1st metatarsal length.

3.6 Qualitative and Quantitative

3.6.1 Observations

The number of bands of the anterior talofibular (ATFL), posterior tibiotalar (PTTL) and anterior tibiotalar (ATTL) ligaments were observed and noted. A multiband ligament was considered when separate fibre groups of a ligament had different proximal or distal bony attachments and/or different directions (orientation); most fasciculated ligaments had bands united at their origin (Figure 3.8).

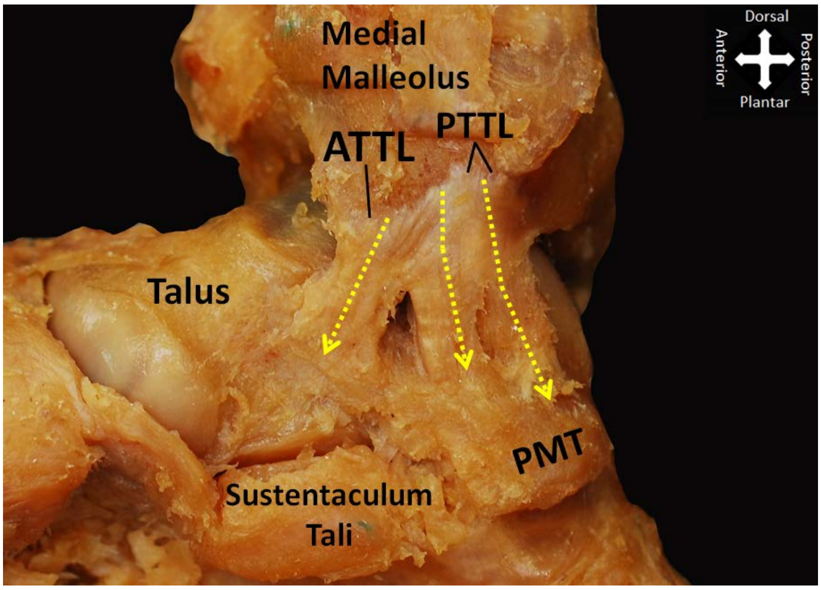

Figure 3.8 Fasciculation of the deep part of the deltoid ligament: ATTL, anterior tibiotalar ligament; PTTL, posterior tibiotalar ligament; PMT, posteromedial tubercle.

The superior band of the ATFL was considered to be its main component when there was more than one band, while the inferior and middle bands were referred to as the inferior band of the anterior talofibular ligament (IATFL) and the middle band of the anterior talofibular ligament (MATFL) respectively. When the PTTL had two or three bands they were referred to APTTL (anterior band), MPTTL (middle band) and PPTTL (posterior band). The anterior band of the ATTL was referred to as the AATTL, while the posterior band was referred to as the PATTL.

To differentiate between the PTTL and ATTL, the following attachments were used: the ATTL band originated from the medial part or tip of the anterior colliculus of the medial malleolus, while the PTTL originated between the posterior edge of the anterior colliculus and the posterior colliculus of the medial malleolus. The superficial bands of the deltoid ligament covering the individual deep bands were observed and measurements taken. When a ligament had more than one band they were not attached continuously in most cases with separation occurring at different lengths: the form of the separation was studied and documented by measuring the length of the separation distal to the proximal and proximal to the distal attachments (Figure 3.9).

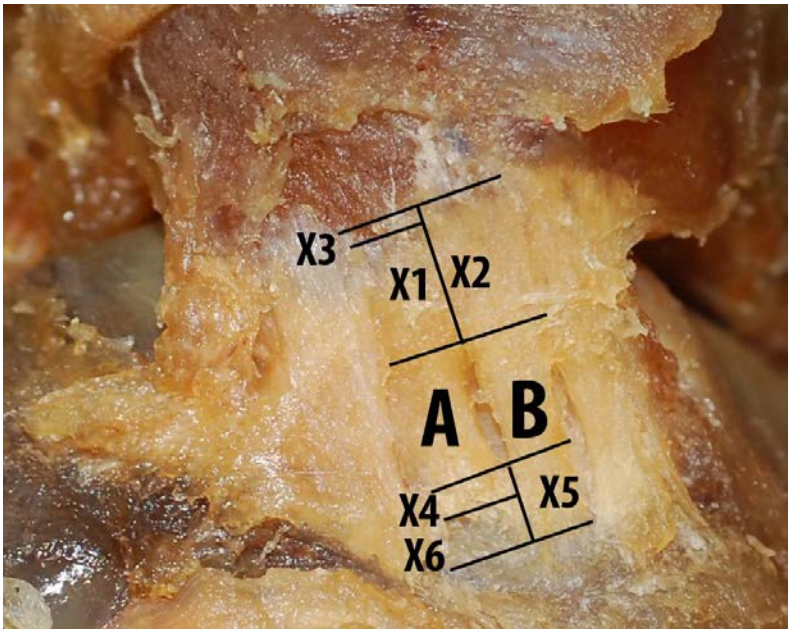

Figure 3.9 Separation of the different bands; ligament A separates from ligament B proximally X1 mm distal to ligament A proximal attachment; ligament A separates from ligament B distally X4 proximal to ligament A distal attachment; Ligament B separates from ligament A proximally X2 mm distal to ligament B proximal attachment with X3 mm free proximally, ligament B separates from ligament A distally X5 mm proximal to ligament A distal attachment with X6 mm distally free.

Ligament orientation and direction (Figure 3.8) was observed with the ankle passively placed in neutral, dorsiflexion, plantarflexion, inversion and eversion. Photographs were taken to document ligament appearance, band number and variations, proximal and distal attachments and the relation to other ligaments and bony landmarks. All LCL measurements were taken with the MCL intact and vice versa. However, deep MCL measurements were taken after removing the superficial part of the MCL, while the TCL and STTL had their measurements taken after removing the TSL and TNL, although the LCL was intact. Finally, PTFL true length, width, thickness, bony attachment lengths and the proximal insertion were all investigated after sectioning the MCL and disarticulating the ankle joint. Not all measurements were undertaken on all specimens due to a number of factors, including movement limitation (joint stiffness), ligament intactness and pre-mortem osteoligamentous degeneration that may occurred due to the effect of aging.

3.6.2 Ligament Dimensions

Total ligament length was considered as the length along the midline of the ligament or the individual band from the most proximal to the most distal bony attachment points (Figure 3.10). The exception to this was measurement of the TSL, which was taken between the proximal bony attachment and the last point of attachment to the sustentaculum tali when attached to it, otherwise the measurement was taken to where the ligament blended with the connecting fibres of the talocalcaneonavicular (spring) ligament.

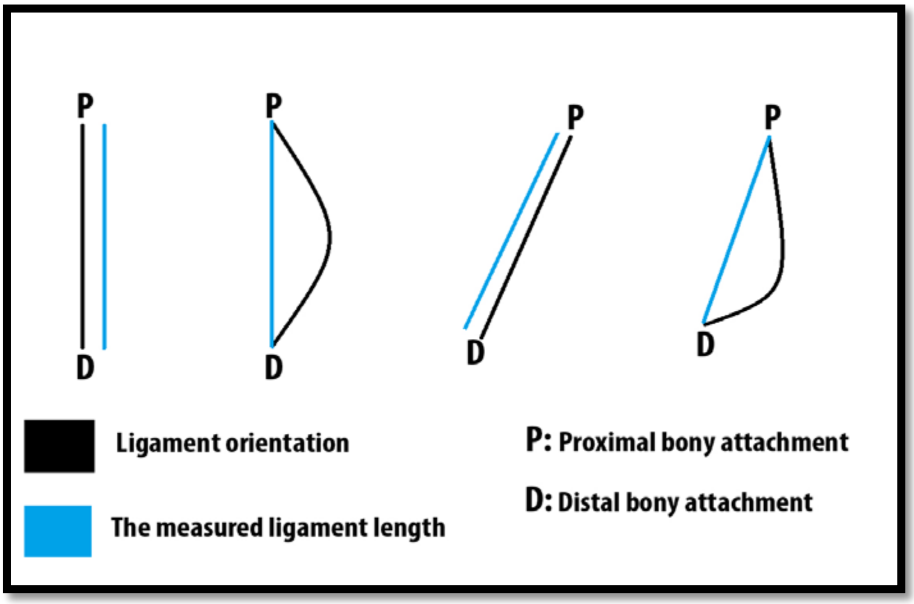

Figure 3.10 Measuring ligament length in different orientations from the most proximal to the most distal bony attachments.

The true length of the PTFL (Figure 3.11) was measured after dislocating the ankle joint with the PTFL still attached to the fibula and talus. This methodology was adopted as it was not possible to measure the total length of the PTFL with the ankle intact as the most proximal part of the ligament was hidden.

Length was measured with the ankle passively placed in all five joint positions. Firstly, the ankle was placed in neutral, which was done by placing the foot at an angle of 90^0 to the leg (Figure 3.3). Then the length was measured with the foot placed in maximal dorsiflexion, maximal plantarflexion, maximal inversion and maximal eversion. The ligaments may become shortened or folded; nevertheless, measurements were taken between the proximal and distal insertion points without regard to the orientation of the ligament.

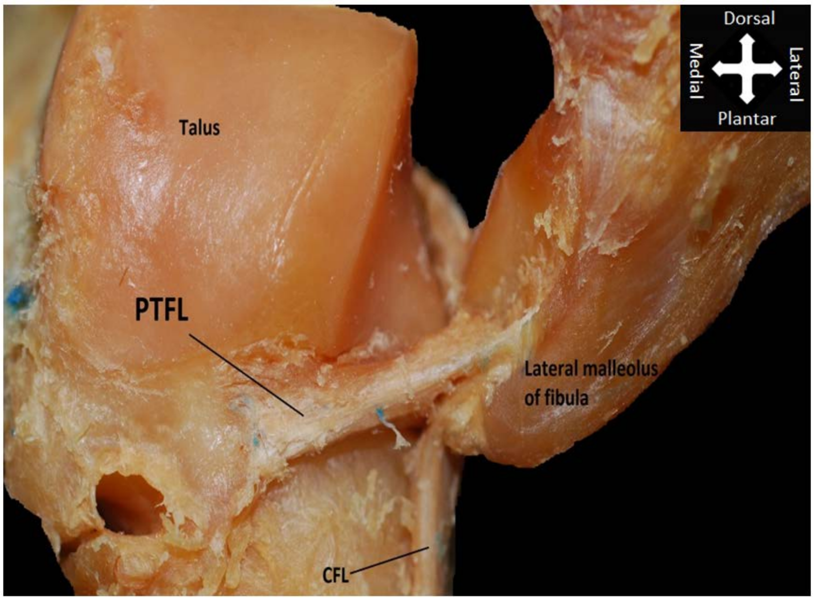

Figure 3.11 Measuring the posterior talofibular ligament (PTFL) true length after dislocating the ankle joint.

Each ligament or band width was measured separately at three different points: at its proximal attachment, at the midlength of each band and at its distal attachment. TSL distal width was taken at the point where the ligament blended with the fibrous layer connecting it to the spring ligament, measurement of the distal width at the end of the attachment was not possible due to expansion of its distal insertion to the sustentaculum tali, as well as the connecting fibres to the spring ligament. Ligament thickness was measured at the midpoint of the ligament, defined from the total length in plantarflexion for the ATFL, CFL, TNL, TSL, TCL and ATTL, and in dorsiflexion for the STTL and PTTL and for the true length of the PTFL.

3.6.3 Bony Attachment Site Length

The bony attachment lengths of the ATFL, CFL, TNL, TSL, TCL and ATTL were determined in maximal plantarflexion, while the STTL and PTTL were measured in maximal dorsiflexion: the PTFL bony attachment lengths were taken after dislocating the ankle joint. The non-bony attachment length (NBA) or the free length (Figure 3.12 and 3.13) was taken as the distance between the first point of attachment proximally distal to the most superior fibres attaching proximally and the first point of bony attachment distally proximal to the most inferior fibres attaching distally. Distal bony attachment length (DBA) was taken as the distance between the ligament's fibres that had a bony attachment distally and the last ligament fibres at the distal point of the bony attachment (Figure 3.12). Moreover, subtracting the DBA and NBA from the ligament's total length enabled determination of the proximal bony attachment length (PBA).

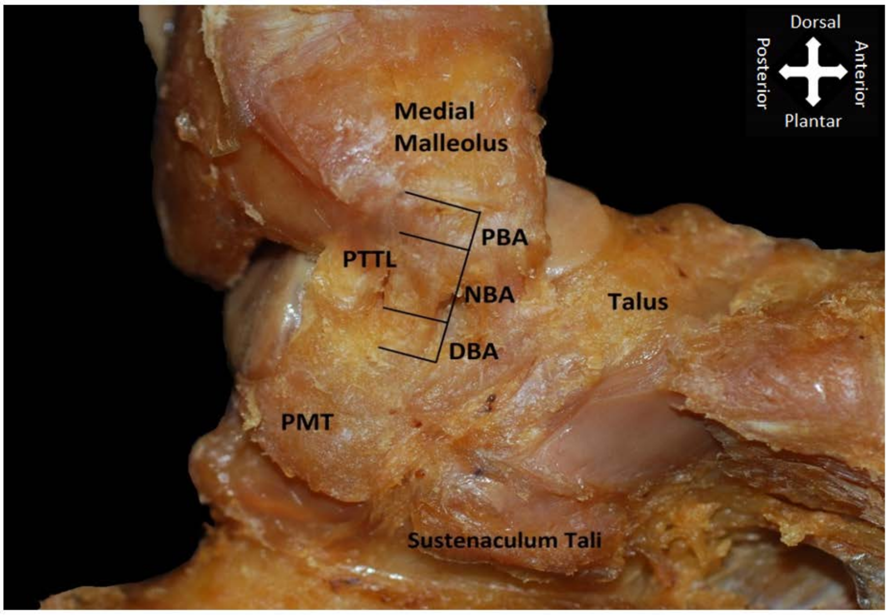

Figure 3.12 Bony attachment lengths of the posterior tibiotalar ligament (PTTL).

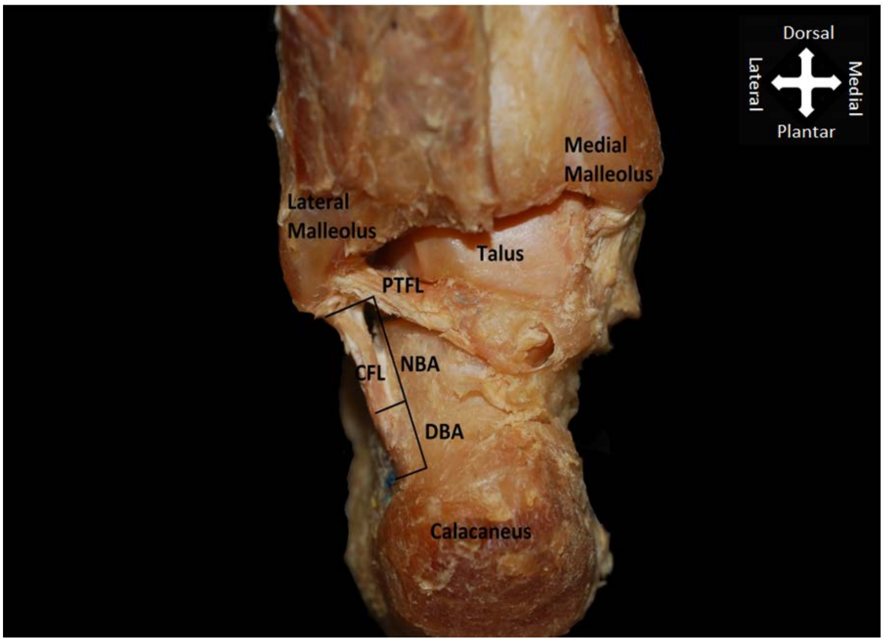

Figure 3.13 No bony attachment (NBA) and distal bony attachment (DBA) lengths of the calcaneofibular ligament (CFL).

TSL (Figure 3.14) NBA was measured to the point where the ligament blended with the fibrous tissues extending to the spring ligament. However, the TSL DBA was measured at the point of blending where the ligament terminated distally. The TNL (Figure 3.14) showed variation in attaching to different bones, therefore the ligament was carefully identified and measurements taken each time it had a bony attachment or was free of attachment. For instance, in most cases the TNL had two NBAs: one superior after leaving the proximal bony attachment and before attaching to the talus and another inferior after the last attachment to the talus along its course. DBA attachment was then measured, which was usually to the navicular (NaBA), but in some cases when the distal attachment was shared between the talus and navicular, the DBA had both measurements taken one to the talus (TaBA) and one to the navicular (NaBA).

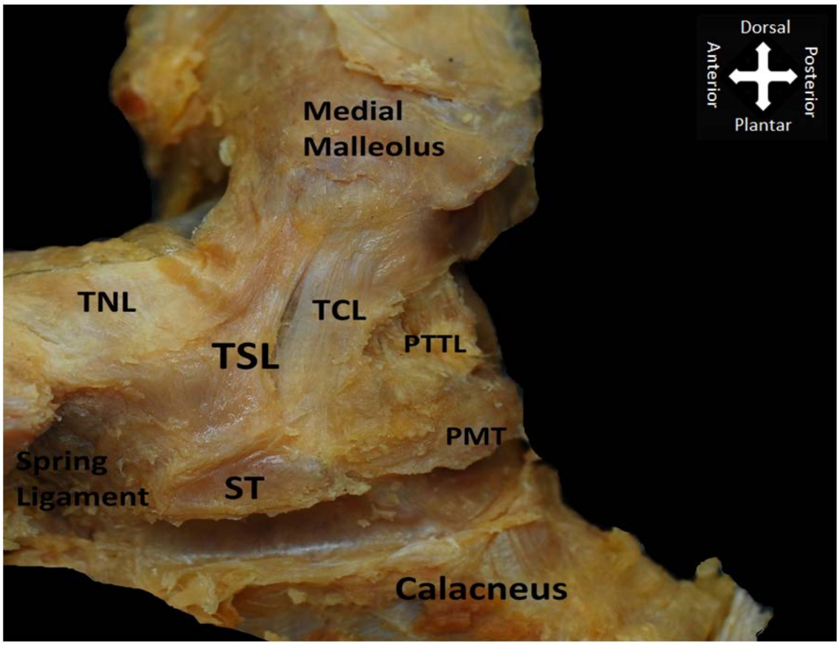

Figure 3.14 Superficial component of the deltoid ligament: TNL, tibionavicular ligament; TSL, tibiospring ligament; TCL, tibiocalcaneal ligament; PTTL, deep posterior tibiotalar ligament; ST, sustentaculum tali of the calcaneus; PMT, talar posteromedial tubercle.

3.6.4 Determination and Measurement of the Proximal Attachment

To provide a better description of the origin of each ligament, a constant method was applied. ATFL and CFL proximal attachments to the fibula were determined in relation to the tip of the lateral malleolus. The distances between the midproximal attachments of the ATFL and CFL and tip of the lateral malleolus (Figure 3.15) were measured using a digital caliper in the transverse plane; a line drawn parallel to the transverse plane of the foot. Additionally, the angle between the midproximal attachment and the lateral malleolar tip was also measured.

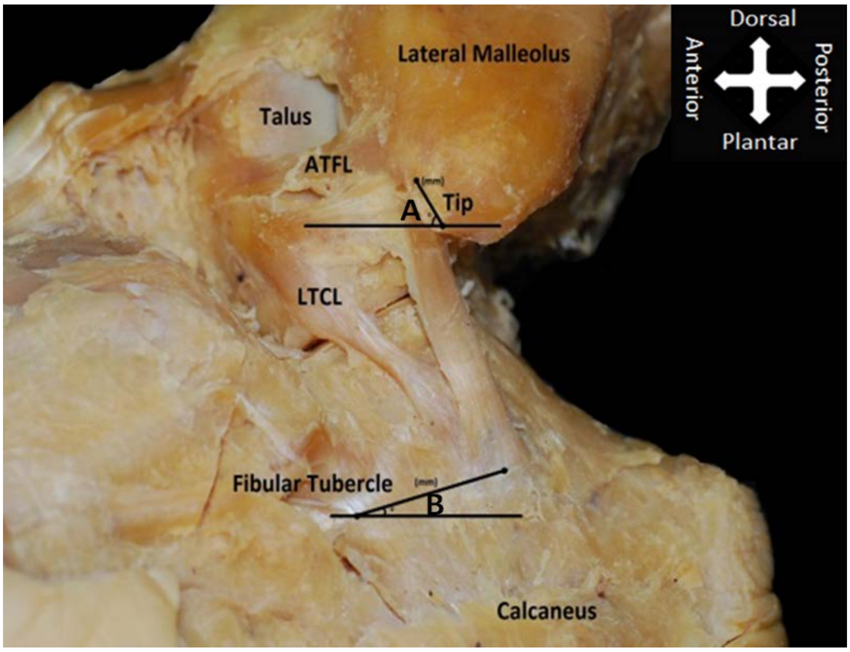

Figure 3.15 Anterior talofibular ligament (ATFL) proximal attachment and calcaneofibular ligament (CFL) distal attachment: A; angle between the lateral malleolar tip and proximal attachment of the ATFL, B; angle between the fibular tubercle of the calcaneus and distal attachment of the CFL

The exact proximal insertion of the PTFL was identified by measuring the distance between the midpoint of its proximal origin in the malleolar fossa to the tip of the lateral malleolus. When either the TCL and/or the STTL proximal attachment were proximal to the intercollicular groove, the distance between the border of the intercollicular groove and the midproximal attachment of the STTL and TCL was measured. This distance was abbreviated as MSMSBIG, i.e. the proximal attachment inserted on the medial surface of the medial malleolus superior to the border of the intercollicular groove.

To identify the exact proximal insertion of the deep component of the MCL, the ankle was dislocated and the ligament's proximal attachment viewed from the lateral surface of the medial malleolus in relation to the anterior colliculus, intercollicular groove and posterior colliculus (Figure 3.16).

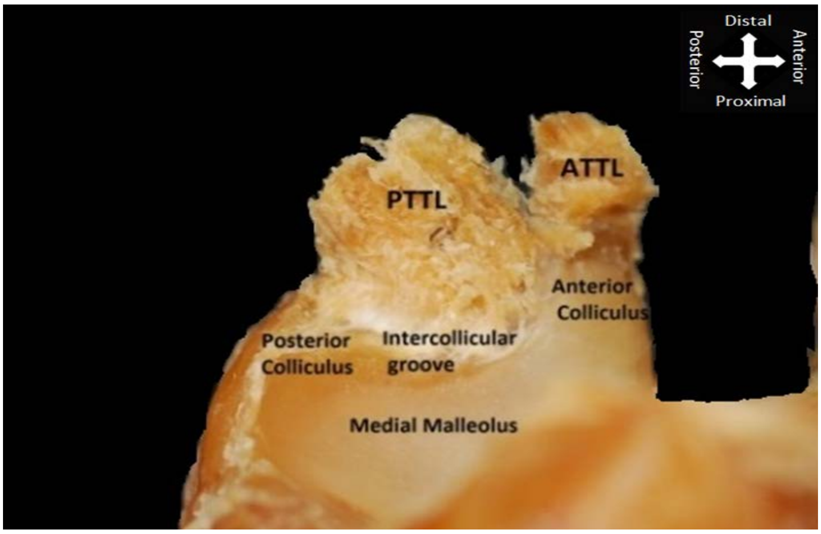

Figure 3.16 Proximal attachment of the deep component of the deltoid ligament: PTTL, posterior tibiotalar ligament; ATTL, anterior tibiotalar ligament.

3.6.5 Determination and Measurement of the Distal Attachment

The distal attachment of the individual ATFL bands were identified in relation to a bony landmark on the talus, the anterolateral malleolar line (ALML) (Figure 3.17). This was achieved by measuring the distance between the ALML and the middistal attachment of each ATFL band which inserted anteromedial to the ALML: this was performed after disarticulating the ankle joint but maintaining the distal part of the ATFL attached. The ALML was the line that forms the anterior border of the lateral malleolar articular surface, which extends between the most proximal point of the anterior part of the lateral malleolar articular surface to the most distal point in the talar body.

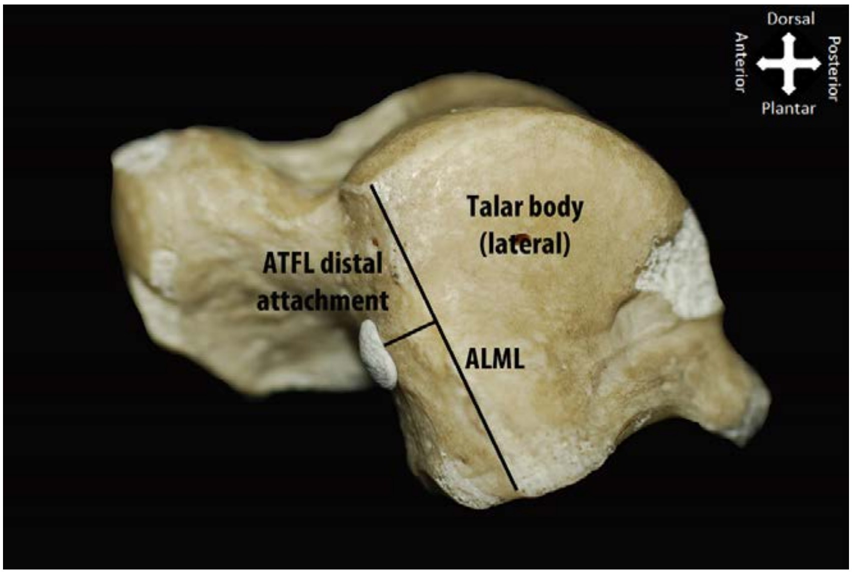

Figure 3.17 Distance between the mid distal attachment of the anterior talofibular ligament (ATFL) and anterolateral malleolar line (ALML) of the talus.

The fibular tubercle on the calcaneus was used as the bony landmark to identify the insertion of the CFL (Figure 3.15). The distance and angle between this tubercle and the midpoint of the distal insertion of the CFL was measured in the transverse plane: a line parallel to the transverse plane was drawn through the fibular tubercle.

Defining the exact distal insertion of the deep compartment of the MCL may aid in understanding the area of the attachment and the way these bands contribute to providing the appropriate medial stability of the ankle joint. Therefore, the exact distal attachment points of the different bands were identified in relation to the posteromedial tubercle (Figure 3.18). A line parallel to the transverse plane was drawn through the posteromedial tubercle of the talus and another line was drawn to the midpoint of the distal attachment of each band of the PTTL and ATTL. The angle and distance were then measured providing an exact insertion of these ligaments on the talus.

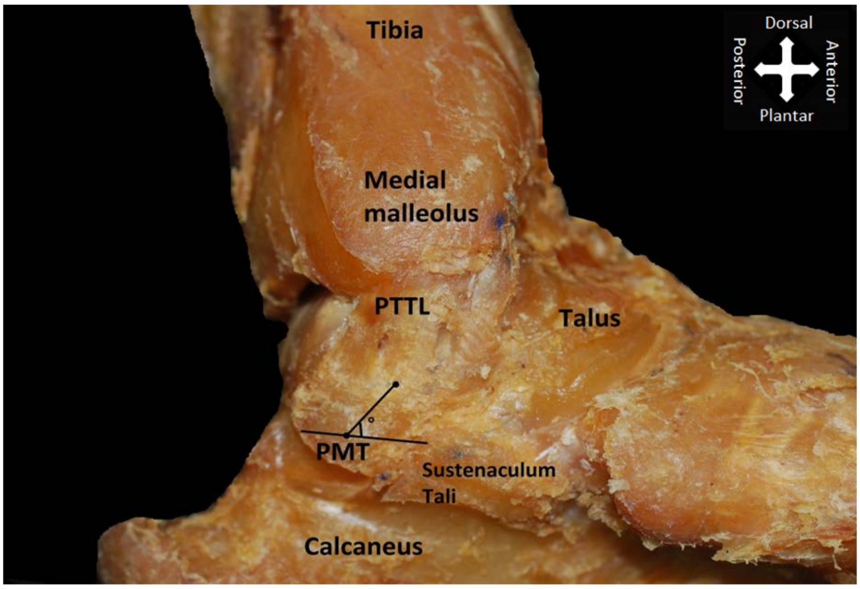

Figure 3.18 Posterior tibiotalar ligament (PTTL) distal attachment.

3.6.6 Angles and Relations

An understanding of the interaction between the ATFL and CFL in generating an efficient stabilising function may be gained by knowing the relation and angle between the ATFL and CFL (Figure 3.19). This angle was measured at the proximal attachment, being between the anterior edge of the CFL and the inferior edge of the ATFL.

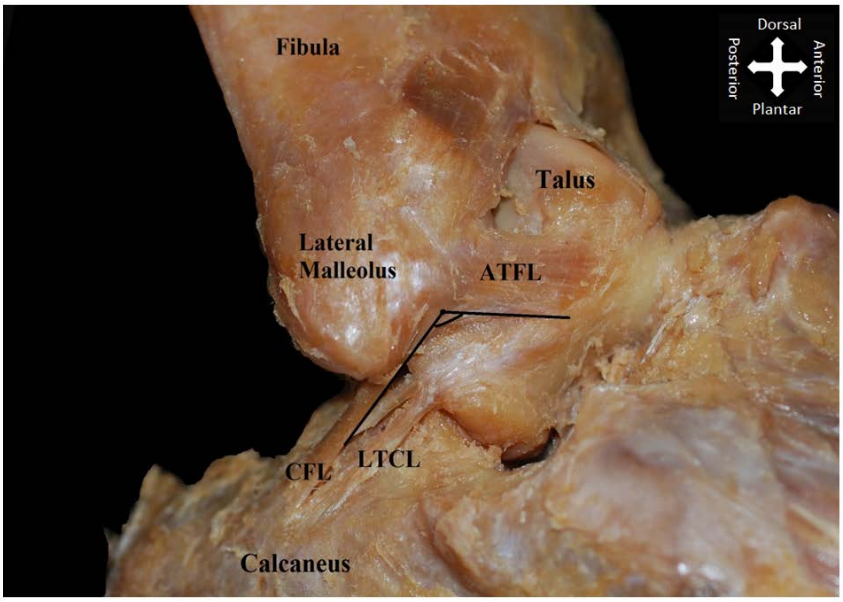

Figure 3.19 Angle between the anterior talofibular ligament (ATFL) and calcaneofibular ligament (CFL): LTCL, lateral talocalcaneal ligament.

3.6.7 Reliability

The repeatability of the methodology and the reliability of the measurements taken of the LCL were assessed by randomly selecting five feet from those studied, with most measurements being taken five times; three measurements were taken on a three separate occasions by the researcher, while two other individuals made the same measurements on two other occasions. In addition, five other feet were chosen randomly on which measurements for the MCL were repeated three times by the researcher on three separate occasions. Then, a reliability analytical test (Cronbach's Alpha (α)) was conducted using IBM SPSS Statistics software (Version 21.0.0.0 © Copyright IBM Corporation and other(s) 1989, 2012).

3.6.8 Statistical Analysis

The collected data in this study was statistically analysed with the help and consultation of an expert local (University of Dundee) statistician; this helped to choose and apply the most appropriate statistical test with respect to the data collected. The descriptive results such as the frequency, mean, range, standard deviation were obtained using Microsoft Excel 2010 software, as well as IBM SPSS Statistics software (Version 21.0.0.0 © Copyright IBM Corporation and other(s) 1989, 2012), while all other analyses were conducted using SPSS software. The Independent Sample T-Test was used to determine significant differences between two independent groups. When there were more than two groups a One-Way ANOVA was used to determine differences. When the One-Way Anova reported a significant difference, a Post Hoc test was used to identify where the differences were between groups.

Crosstabs and the Chi Square test were used to identify the relationship between ligament band number and gender and foot side. Other relationships with respect to gender and foot side were performed on the origin and insertion of the TNL, TCL and STTL, ATTL existence and the part of the sustentaculum tali that the TSL had a distal attachment to. The general linear model was used as an extension of the T-Test in order to compare several sets of measurements that were taken. In the present study, a significant difference was accepted when the P value was less than 0.05. Finally, the current study used the Pearson Correlation test with its correlation coefficient in order to investigate possible correlations between the different parameters.

4 Results

4.1 Reliability

Cronbach's Alpha test showed that there was a high level of internal consistency and that there was no difference for a single observer between the same measurements taken on separate occasions: $\alpha = 0.998$ (Table 4.1) and $\alpha = 0.996$ (Table 4.2). There was also no difference in the measurements taken by different observers (Table 4.1) ($\alpha = 0.997$). These results indicate that the measurement methodology was used was reliable and repeatable. One anomaly was found in the length and width of one middle band (MATFL) in a three band ATFL among the five randomly selected feet; there was no explanation for this anomaly as measurements were not checked in order to accurately test the reliability. However, this difference had no affect on the overall reliability ($\alpha = 0.998$ and $\alpha = 0.996$), which showed very good reliability among all the observers suggesting the reliability and repeatability of the measurements that were taken.

Table 4.1 Measurements of the lateral collateral ligaments (LCL) by a single observer (researcher) on three separate occasions (α = 0.998) and two different observers (α = 0.997) (mean ± standard deviation in mm): N, neutral; DF, dorsiflexion; PF, plantarflexion; IN, inversion; EV, eversion; P, proximal; M, middle; D, distal; ATFL, anterior talofibular ligament; IATFL, inferior band of ATFL; MATFL, middle band of ATFL; CFL, calcaneofibular ligament; PTFL, posterior talofibular ligament.

	Observer 1 (Day 1)	**Observer 1 (Day 2)**	**Observer 1 (Day 3)**	**Observer 2**	**Observer 3**
ATFL Length (N)	23.07 ± 3.73	22.19 ± 1.62	21.76 ± 3.54	21.65 ± 0.99	19.84 ± 2.20
ATFL Length (DF)	22.98 ± 3.17	21.36 ± 2.68	20.80 ± 3.84	21.87 ± 1.92	19.61 ± 2.0
ATFL Length (PF)	22.57 ± 2.89	21.67 ± 2.52	22.95 3.45	22.32 ± 1.43	20.81 ± 2.07
IATFL Length (N)	18.58 ± 1.73	17.56 ± 0.76	18.03 ± 3.61	17.59 ± 0.41	15.68 ± 2.93
IATFL Length (DF)	18.23 ± 2.29	15.45 ± 0.84	17.37 ± 3.12	17.04 ± 1.97	15.68 ± 2.42
IATFL Length (PF)	17.88 ± 1.79	18.01 ± 1.08	18.24 ± 1.42	16.81 ± 1.72	17.25 ± 2.72
MATFL Length (N)	19.4	18.44	18.7	19.63	13.58
MATFL Length (DF)	17.86	18.16	16.57	17.13	17.99
MATFL Length (PF)	22.13	18.43	19.57	18.23	16.35
ATFL Width (P)	4.77 ± 1.35	4.38 ± 1.18	4.58 ± 0.61	5.15 ± 0.65	4.35 ± 1.56
ATFL Width (M)	3.87 ± 0.97	3.65 ± 0.90	3.99 ± 1.16	4.29 ± 1.06	4.10 ± 1.26
ATFL Width (D)	3.92 ± 0.62	3.48 ± 0.65	3.34 ± 0.46	4.39 ± 1.24	5.02 ± 1.64
IATFL Width (P)	3.94 ± 1.45	3.97 ± 1.31	4.17 ± 1.11	4.31 ± 0.86	4.98 ± 1.50
IATFL Width (M)	4.13 ± 1.12	4.64 ± 1.16	4.64 ± 1.18	4.07 ± 1.14	4.99 ± 2.47
IATFL Width (D)	3.43 ± 0.25	3.63 ± 0.64	3.19 ± 0.46	3.0 ± 0.53	3.43 ± 1.23
MATFL Width (P)	1.79	2.42	2.51	3.58	2.64
MATFL Width (M)	2.82	2.64	2.17	2.63	2.47
MATFL Width (D)	2.87	3.99	2.41	2.09	3.81
CFL Length (N)	25.19 ± 3.57	26.44 ± 3.28	25.47 ± 2.97	24.84 ± 3.33	27.23 ± 4.05
CFL Length (DF)	27.58 ± 2.78	27.84 ± 3.09	27.82 ± 2.84	27.67 ± 2.11	29.40 ± 3.77
CFL Length (PF)	24.05 ± 2.95	23.52 ± 3.08	23.78 ± 3.82	24.25 ± 1.91	26.73 ± 2.54
CFL Width (P)	3.79 ± 0.49	3.72 ± 0.57	2.95 ± 0.66	4.25 ± 0.90	3.55 ± 0.89
CFL Width (M)	4.48 ± 0.83	4.43 ± 0.74	4.34 ± 0.59	4.41 ± 0.57	4.39 ± 0.74
CFL Width (D)	6.67 ± 0.48	6.38 ± 0.76	6.52 ± 0.95	7.03 ± 0.96	6.67 ± 1.21
PTFL Length (N)	18.96 ± 4.19	18.50 ± 3.91	19.88 ± 3.11	16.5 ± 1.64	17.07 ± 5.32
PTFL Length (DF)	20.65 ± 4.23	20.78 ± 3.30	21.31 ± 2.88	19.35 ± 2.16	19.58 ± 5.84
Angle between ATFL & CFL	125° ± 8°	120° ± 5°	127.8° ± 7°	125° ± 14°	122° ± 14°

Table 4.2 Measurements of the medial collateral ligaments (deltoid) by a single observer (researcher) on three separate occasions (α = 0.996) (mean ± standard deviation in mm): N, neutral; DF, dorsiflexion; PF, plantarflexion; IN, inversion; EV, eversion; PMT, talar posteromedial tubercle; TSL, tibiospring ligament; TNL, tibionavicular ligament; APTTL, anterior band of the posterior tibiotalar ligament (PTTL); MPTTL, middle band of PTTL; PPTTL, posterior band of PTTL; ATTL, anterior tibiotalar ligament.

	Occasion 1	**Occasion 2**	**Occasion 3**
TSL Length (N)	35.21 ± 6.29	35.65 ± 5.42	35.56 ± 5.18
TSL Length (DF)	33.39 ± 4.58	34.94 ± 5.49	34.74 ± 5.01
TSL Length (PF)	36.85 ± 6.66	37.19 ± 6.59	35.89 ± 5.69
TSL Length (IN)	36.36 ± 7.31	36.33 ± 7.10	36.39 ± 5.75
TSL Length (EV)	34.13 ± 6.31	35.21 ± 5.36	34.79 ± 4.70
TNL Length (N)	29.54 ± 3.73	30.34 ± 3.74	29.51 ± 3.33
TNL Length (DF)	29.12 ± 3.98	30.28 ± 5.14	31.26 ± 4.47
TNL Length (PF)	43.79 ± 3.95	43.97 ± 4.08	43.30 ± 3.57
TNL Length (IN)	43.05 ± 3.97	42.8 ± 4.46	43.81 ± 4.13
TNL Length (EV)	28.35 ± 3.60	27.65 ± 3.77	27.50 ± 4.14
APTTL Length (N)	14.83 ± 2.33	13.69 ± 2.33	14.72 ± 2.64
APTTL Length (DF)	14.98 ± 2.71	15.13 ± 2.51	15.56 ± 2.62
APTTL Length (PF)	10.49 ± 1.44	10.71 ± 1.97	11.30 ± 1.95
APTTL Length (IN)	10.48 ± 0.92	10.96 ± 1.58	11.02 ± 2.29
APTTL Length (EV)	14.79 ± 2.65	15.26 ± 2.20	15.12 ± 2.79
MPTTL Length (N)	14.48 ± 1.33	14.34 ± 0.93	15.15 ± 0.75
MPTTL Length (DF)	14.69 ± 0.93	15.27 ± 1.00	16.20 ± 0.66
MPTTL Length (PF)	10.80 ± 1.14	11.49 ± 0.27	11.80 ± 0.61
MPTTL Length (IN)	10.30 ± 1.22	9.91 ± 0.77	10.90 ± 1.35
MPTTL Length (EV)	15.64 ± 0.83	14.55 ± 1.02	16.16 ± 0.64
PPTTL Length (N)	14.21 ± 1.85	13.45 ± 1.65	14.63 ± 1.89
PPTTL Length (DF)	15.6 ± 1.77	15.45 ± 1.08	16.07 ± 1.54
PPTTL Length (PF)	10.07 ± 2.15	9.66 ± 1.66	10.54 ± 1.95
PPTTL Length (IN)	9.1 ± 1.54	9.03 ± 1.48	9.68 ± 1.43
PPTTL Length (EV)	14.94 ± 1.76	15.61 ± 1.49	15.66 ± 1.72
ATTL Length (N)	8.59 ± 4.05	7.81 ± 3.74	7.93 ± 3.66
ATTL Length (DF)	8.07 ± 3.98	8.09 ± 3.62	7.95 ± 3.73
ATTL Length (PF)	9.25 ± 3.86	8.91 ± 3.86	8.85 ± 3.90
ATTL Length (IN)	9.11 ± 3.91	9.39 ± 3.87	8.83 ± 3.61
ATTL Length (EV)	7.76 ± 3.51	8.25 ± 3.87	8.97 ± 3.87
Angle between APTTL distal attachment and PMT	46° ± 23°	45° ± 16°	46° ± 23°
Angle between MPTTL distal attachment and PMT	54° ± 14°	55° ± 13°	55° ± 15°
Angle between PPTTL distal attachment and PMT	87° ± 14°	89° ± 12°	87° ± 13°
Angle between ATTL distal attachment and PMT	31° ± 5°	33° ± 6°	32° ± 5°

4.2 Foot Length, 1st Metatarsal Length and Passive Range of Motion (PROM)

The specimens examined had a mean foot length of 200.9 ± 18.2 mm (range 175 mm to 253 mm), with the mean length for males being 215.9 ± 18.7 mm and for females 190.1 ± 8 mm: there was a significant difference between males and females ($P < 0.001$). However, there was no difference in foot length between the right and left sides. A correlation was observed between foot length and 1st metatarsal length ($r = 0.642$, $r^2 = 0.41$, $P < 0.001$).

The mean length of the 1st metatarsal was 63.45 ± 4.43 mm (range 54.72 mm to 75.62 mm), there being a significant difference in length ($P < 0.001$) between males (66.75 ± 4.13 mm) and females (61.42 ± 3.26 mm), but not between the right (63.92 ± 4.87 mm) and left (62 ± 3.99 mm) sides.

The mean passive ranges of motion (PROM) after dissection were: for dorsiflexion 6° ± 3°, for plantarflexion 40° ± 7°, for inversion 20° ± 6°, for eversion 11° ± 4°, for isolated inversion 17° ± 6°, and for isolated eversion 9° ± 3°. No differences in PROM were found between males and females or between the right and left sides.

4.3 Anterior Talofibular Ligament (ATFL)

4.3.1 Band Number of the Anterior Talofibular Ligament (ATFL)

One (17.2%), two (62.5%) and three (20.3%) band forms of the ATFL were observed (Figures 4.1, 4.2, 4.3, 4.4) with multiple bands usually having different distal insertions and/or different fibre orientations, although bands were not necessarily completely separated from each other. The single band form was observed unilaterally in 40% of specimens and bilaterally in 60% of specimens; the two band form was similarly distributed, being unilateral in 38.89% and bilateral in 61.1% of specimens; while the three band form was observed to be unilateral and bilateral in 84.6% and 15.4% of specimens respectively.

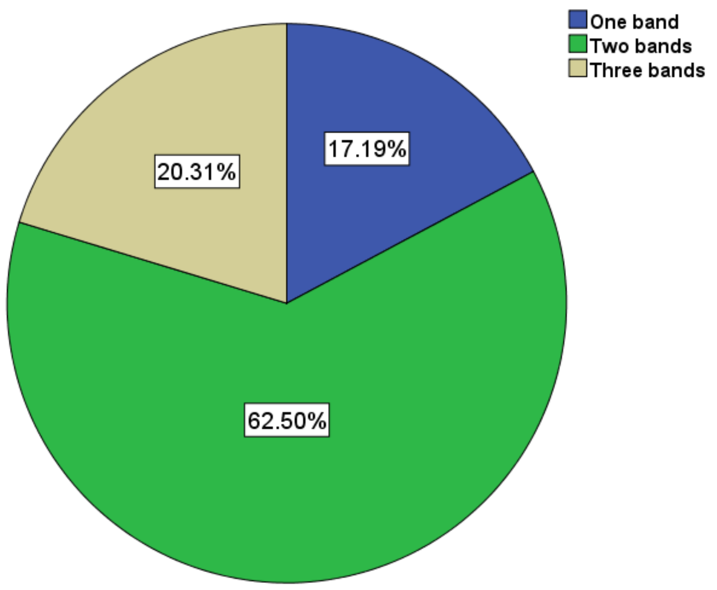

Figure 4.1 Band Number of the Anterior Talofibular Ligament (ATFL)

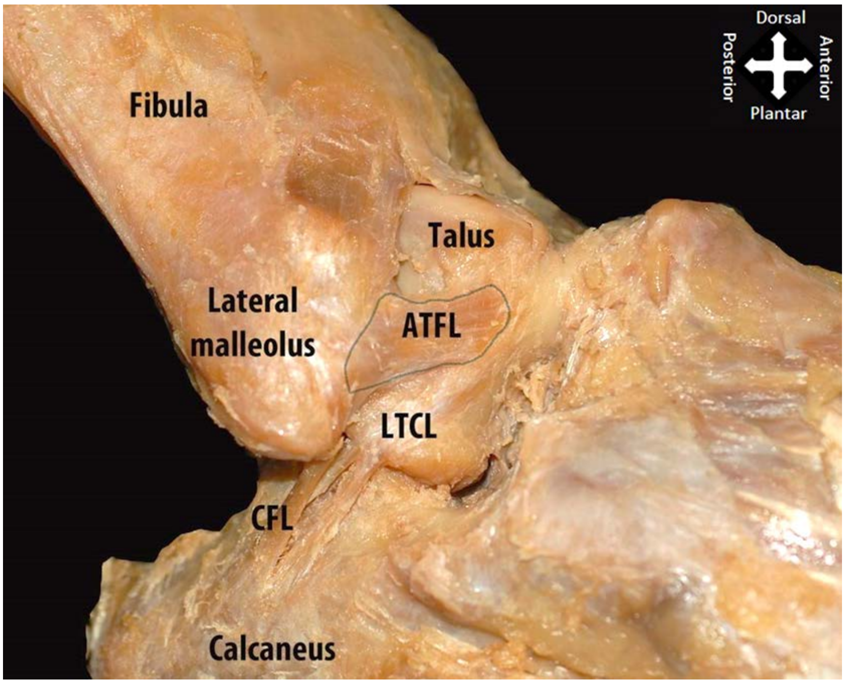

Figure 4.2 One band form of the anterior talofibular ligament (ATFL): LTCL, lateral talocalcaneal ligament; CFL, calcaneofibular ligament.

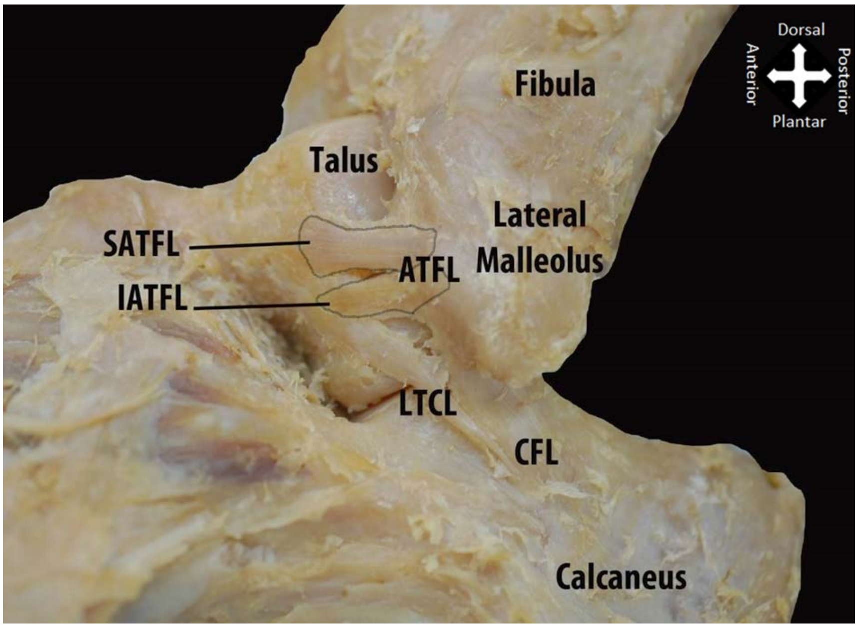

Figure 4.3 Two band form of the anterior talofibular ligament (ATFL): SATFL, superior anterior talofibular band; IATFL, inferior anterior talofibular band; LTCL, lateral talocalcaneal ligament; CFL, calcaneofibular ligament.

The distribution of band form differed slightly between right and left feet, with right feet having one (12.5%), two (65.6%) and three (21.9%) bands, while left feet had one (21.9%), two (59.4%) and three (18.8%) bands. The association between ATFL band number and foot side was examined and no association found. However, there was an association between ATFL band number and gender ($r = 0.316$, $r^2 = 0.10$ $P = 0.042$), with the two band form being more common in females (70% of all two band specimens), while the three band form was more common in males (69.2% of all three band specimens) (Figure 4.5).

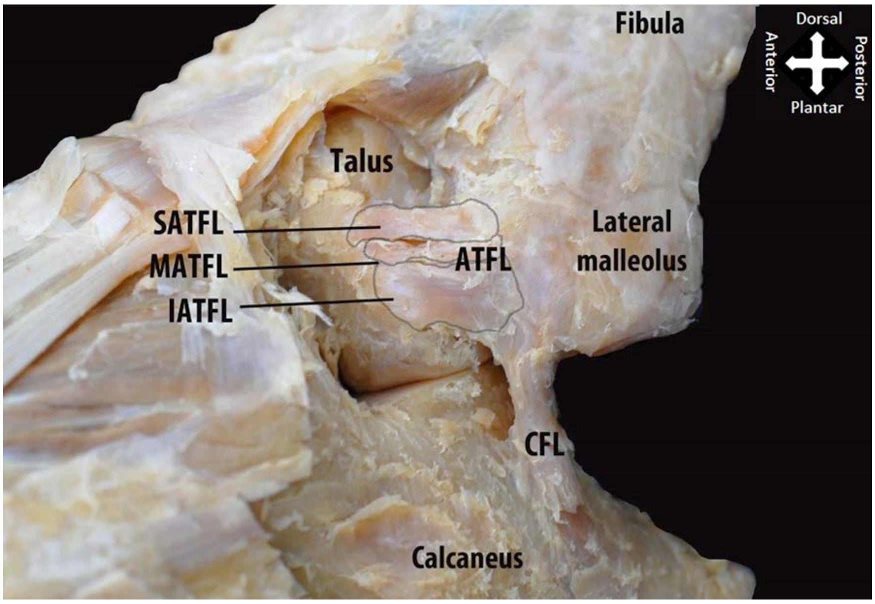

Figure 4.4 Three band form of the anterior talofibular ligament (ATFL): SATFL, superior anterior talofibular band; MATFL, middle anterior talofibular band; IATFL, inferior talofibular; CFL, calcaneofibular ligament.

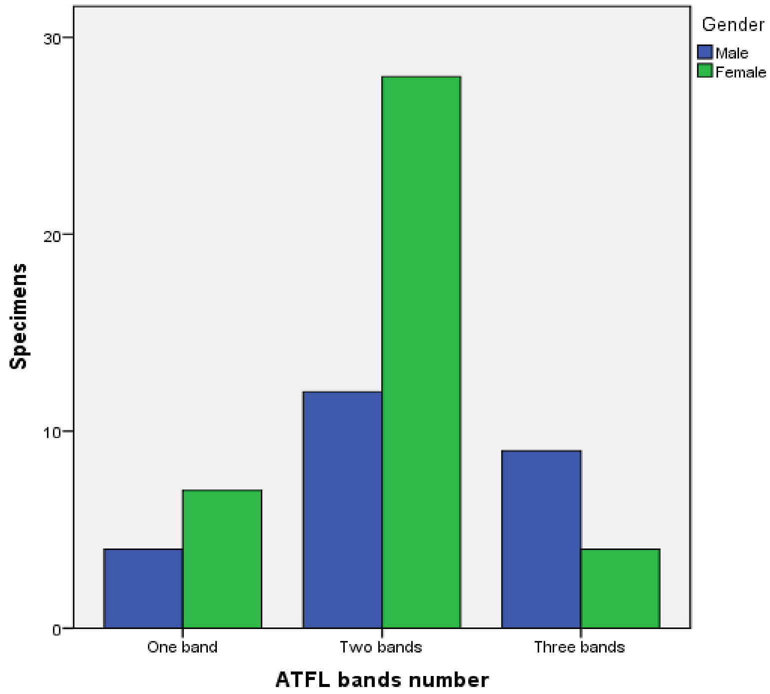

Figure 4.5 Anterior talofibular ligament (ATFL) band number in males and females.

There were no differences between the number of ATFL bands and age or the maximum PROM in dorsiflexion, plantarflexion, inversion and eversion. However, a significant difference was observed between band number and foot length (P = 0.039), as well as with 1st metatarsal length (P = 0.003) (Table 4.3). Analysis of the different band forms, foot length and 1st metatarsal length showed a significant difference between the three and the one (P = 0.037) and two band (P = 0.017) forms, but no difference between the one and two band forms. This suggests that the three band form of the ATFL is more common in longer feet. In addition, 1st metatarsal length was not different between the one and two band forms; however, in the three band form it was significantly longer than in the one (P = 0.001) and two (P = 0.004) band forms. Therefore, the suggestion is that specimens with longer 1st metatarsals are associated with the three band form of the ATFL.

Table 4.3 Anterior talofibular ligament band number, foot length and 1st metatarsal length: SD, standard deviation.

		N	Mean ± SD	P Value
Foot Length (mm)	One band	9	196 ± 15.8	0.039
	Two bands	37	198.2 ± 15.7	
	Three bands	12	212.8 ± 24.3	
1st metatarsal length (mm)	One band	9	60.92 ± 4.70	0.003
	Two bands	38	62.94 ± 3.35	
	Three bands	12	67.06 ± 5.89	

4.3.2 Proximal Attachment of the Anterior Talofibular Ligament (ATFL)

The ATFL attached proximally to the anterior border of the lateral malleolus (Figure 4.6): the distance and angle between the lateral malleolar tip and the mid proximal attachment of the ligament were 11 ± 3.04 mm and 61° ± 14° respectively. No differences were found in the distance or angle to the lateral malleolar tip with respect to gender, foot side or band number. Furthermore, the mid attachment distance was not correlated with age, foot length, 1st metatarsal length or the angle between the ATFL and CFL at their origin. Correlations between the attachment angle to the tip and foot length ($r = -0.341$, $r^2 = 0.12$, $P = 0.036$) and 1st metatarsal length ($r = -0.358$, $r^2 = 0.13$, $P = 0.027$) were observed.

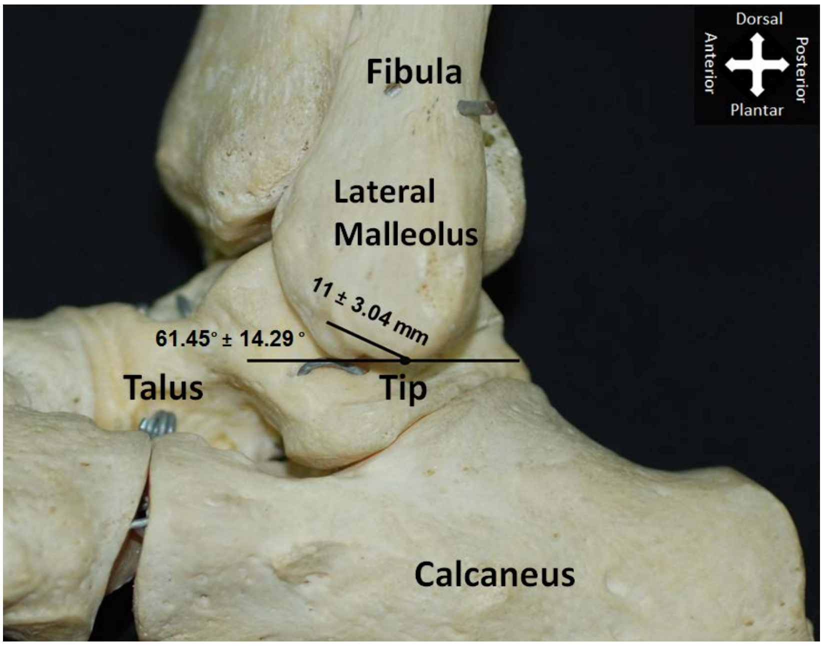

Figure 4.6 Anterior talofibular ligament (ATFL) proximal attachment: the distance and angle between the ATFL mid proximal attachment and the lateral malleolar tip are shown.

The mean angle between the ATFL and CFL proximally was 117° ± 14°: there was no difference in this angle with respect to gender or foot side.. However, a significant difference was found between the angle and ATFL band number (P = 0.007). There was also a significant difference between the one and two band forms (P = 0.003), and between the one and three band forms (P = 0.005), with the one band form possessing a larger angle (131°) compared to the two (115°) and three (113°) band forms. No correlation between the angle between the ATFL and CFL at their origin and age, foot length or 1st metatarsal length was found.

4.3.3 Distal Attachment of the Anterior Talofibular Ligament (ATFL)

The different ATFL bands were attached distally to the body of the talus anteromedial to the anterolateral malleolar line (ALML) (Figure 4.7), with the ATFL inserting 4.46 ± 1.51 mm anteromedial to the ALML (Figure 4.7) and 18.74 ± 2.73 mm superior to the subtalar joint (Figure 4.8). No difference between the distance of the ATFL insertion to the ALML and subtalar joint and gender or foot side were found. Similarly, there were no differences between ATFL band number and the insertion distance to the ALML or subtalar joint. A correlation between the insertion distance to the ALML and the ATFL distal bony attachment length (DBA) ($r = 0.518$, $r^2 = 0.27$ $P = 0.02$) was observed, but not to the insertion distance to the subtalar joint.

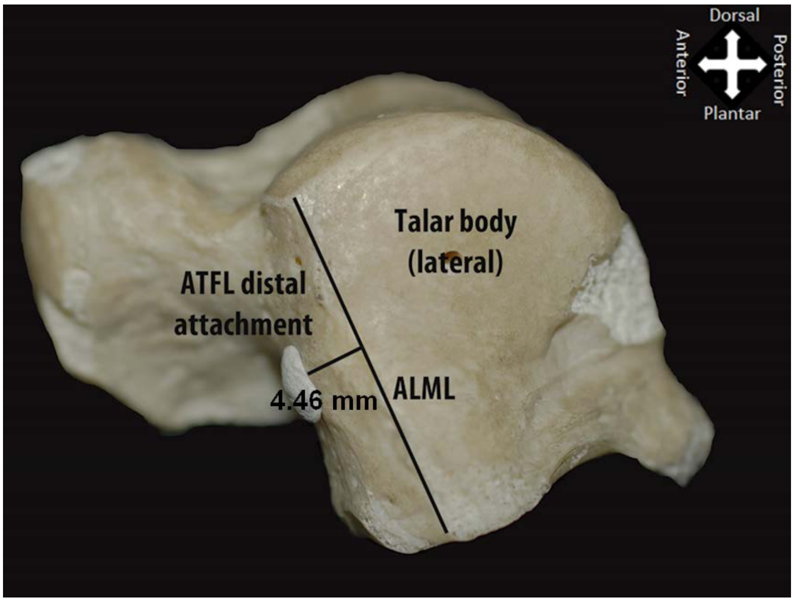

Figure 4.7 Distal attachment of the anterior talofibular ligament (ATFL) on the talar body showing the distance between the ATFL mid distal attachment and anterolateral malleolar line (ALML).

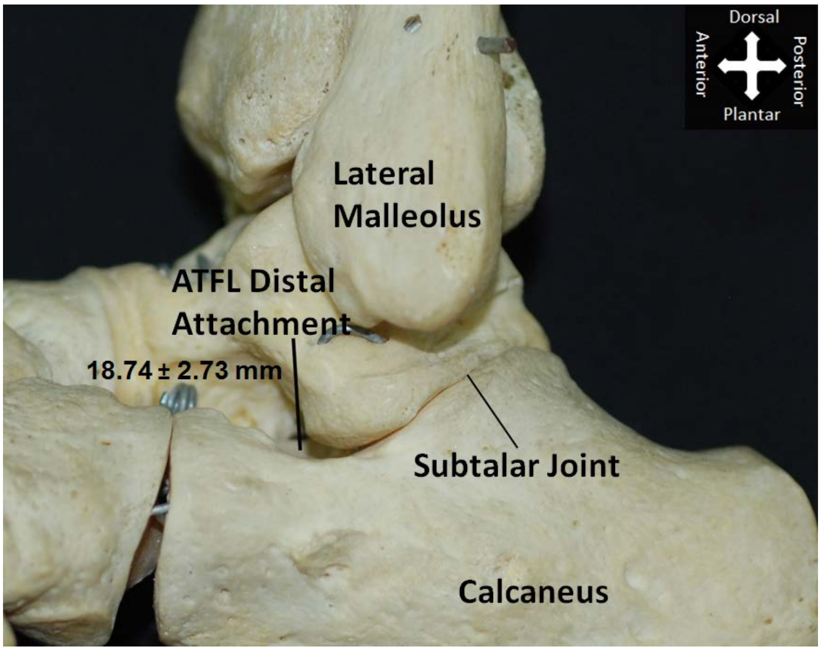

Figure 4.8 Distance between the mid distal attachment anterior talofibular ligament (ATFL) and the subtalar joint.

The inferior band of the ATFL (IATFL) inserted distally to the talar body, with the distance between its insertion and the ALML and subtalar joint being 4.27 ± 2.03 mm and 11.13 ± 2.02 mm respectively. There was a significant difference (P = 0.029) between the IATFL insertion distance to the ALML in males and females, with the IATFL inserting more anterior to the ALML in males (5.14 mm) than females (3.67 mm). However, there was no difference in the IATFL insertion distance to the subtalar joint between males and females. In addition, no difference was found between the IATFL insertion distance to the ALML or the subtalar joint between right and left feet. However, a significant difference was found between ATFL band number and IATFL insertion distance to both the ALML (P = 0.042) and subtalar joint (P = 0.001), with the IATFL insertion in the three band form being more anterior to the ALML (5.45 mm) compared to the two band form (3.88 mm).

The IATFL insertion in the two band form had a longer distance to the subtalar joint (11.85 mm) compared to the three band form (8.00 mm). A correlation was observed between the IATFL insertion distance to the ALML and foot length ($r = 0.403$, $r^2 = 0.16$, $P = 0.015$) as well as 1st metatarsal length ($r = 0.355$, $r^2 = 0.13$, $P = 0.033$). The middle band of the ATFL (MATFL) distal insertion was 4.11 ± 1.19 mm from the ALML and 14.27 ± 2.03 mm from the subtalar joint: there was no difference between these distances with respect to gender or foot side. The only correlations observed were between the MATFL insertion distance to the ALML and the MATFL DBA ($r = 0.891$, $r^2 = 0.79P = 0.043$).

4.3.4 Anterior Talofibular Ligament (ATFL) Orientation

The ATFL crossed medially from the lateral malleolus to the talus, being orientated anterosuperiorly (93.3%), anteroinferiorly (3.3%) and horizontally anterior (3.3%) in neutral (Figure 4.9), plantarflexion and inversion; while it was anterosuperior (96.7%) and anteroinferior (3.3%) in dorsiflexion and eversion (Figure 4.10).

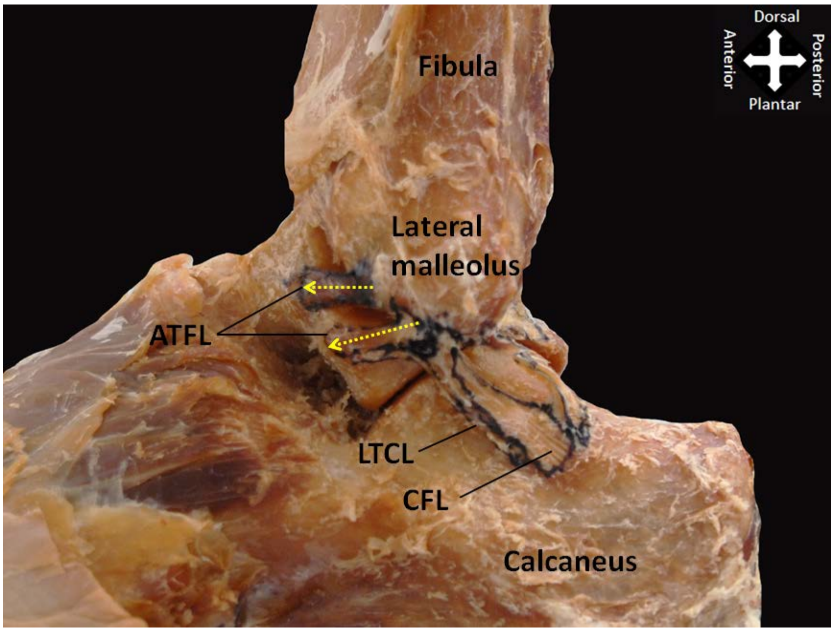

Figure 4.9 Anterior talofibular ligament (ATFL) orientation (yellow dotted arrows) in neutral position: LTCL, lateral talocalcaneal ligament; CFL, calcaneofibular ligament.

The IATFL crossed medially being orientated anterosuperiorly (56%), anteroinferiorly (16%) and horizontally anterior (28%) in neutral and dorsiflexion. In plantarflexion and inversion, it crossed anterosuperiorly (44%), anteroinferiorly (16%) and horizontally anterior (40%). Anterosuperior (60%), anteroinferior (16%) and horizontal anterior (24%) was the IATFL orientation in eversion.

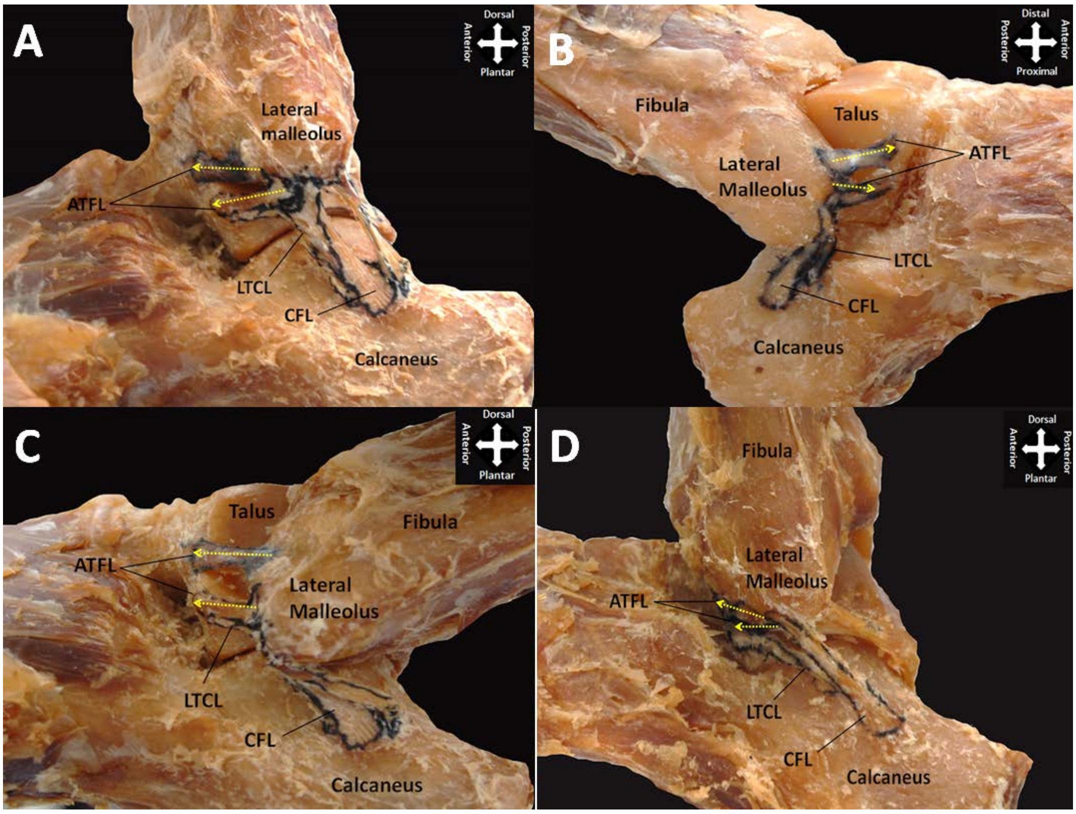

Figure 4.10 Anterior talofibular ligament (ATFL) orientation (yellow dotted arrows) in different joint positions: A, dorsiflexion; B, plantarflexion; C, inversion; D, eversion; LTCL, lateral talocalcaneal ligament; CFL, calcaneofibular ligament.

The MATFL originated from the lateral malleolus crossing medial to the talus, being orientated anterosuperiorly (85.7%) and horizontally anterior (14.3%) in neutral, dorsiflexion and eversion. In plantarflexion and inversion, it was orientated anterosuperiorly and anteroinferiorly in 71.4% and 28.6% of specimens respectively.

4.3.5 Anterior Talofibular Ligament (ATFL) Dimensions

The main ATFL band mean length was 19.58 ± 3.47 mm, with a mid-width and thickness of 4.72 ± 1.41 mm and 0.94 ± 0.35 mm; the total mid-width for the whole ATFL was 8.03 ± 1.92 mm (Table 4.4). Additional band lengths, widths and thicknesses are shown in Table 4.4. The distal total ATFL width was significantly different between genders (P = 0.001), with males (8.24 mm) being greater than females (6.52 mm). However, the various ATFL band lengths, widths and thicknesses were not different between males and females. In addition, there was no difference in ATFL dimensions between the right and left sides. ATFL thickness did not differ between the various ATFL bands.

Table 4.4 Anterior talofibular ligament (ATFL) length, width and thickness (mm): IATFL, inferior anterior talofibular ligament; MATFL, middle anterior talofibular ligament.

	N	Mean ± SD (mm)
ATFL Length (neutral)	59	19.58 ± 3.47
IATFL Length (neutral)	47	15.89 ± 3.11
MATFL Length (neutral)	11	16.78 ± 4.41
ATFL Width (proximal)	63	5.091 ± 1.51
ATFL Width (middle)	62	4.72 ± 1.41
ATFL Width (distal)	63	4.49 ± 1.55
IATFL Width (proximal)	50	4.02 ± 1.49
IATFL Width (middle)	49	3.63 ± 1.29
IATFL Width (distal)	50	2.84 ± 1.04
MATFL Width (proximal)	12	2.61 ± 0.99
MATFL Width (middle)	12	2.3 ± 0.71
MATFL Width (distal)	12	2.35 ± 0.79
ATFL total width (proximal)	68	8.14 ± 3.24
ATFL total width (middle)	62	8.03 ± 1.92
ATFL total width (distal)	62	7.22 ± 2.02
ATFL Thickness	53	0.94 ± 0.35
IATFL Thickness	42	0.57 ± 0.25
MATFL Thickness	10	0.61 ± 0.29

The proximal width of the main ATFL band was significantly different in the various ATFL forms (P = 0.037), with the three band form having the smallest proximal width compared to the one (P = 0.022) and the two band (P = 0.023) forms (Table 4.5). There was also a significant difference in ATFL mid-width between the different bands (P = 0.001), with the one band form being widest compared to the two (P = 0.004) and three (P < 0.001) band forms. The total proximal, middle and distal ATFL widths were also significantly different in the various band forms (P < 0.001). The three band form was the widest in relation to a single band (P <0.001), while the two band form was also wider than the single band form (P < 0.001). In addition, the total mid-width was the greatest in the three band form compared to the one band form (P < 0.001), while the two band form was significantly wider than the single band (P = 0.01). Finally, the total distal width of the three and two band forms was significantly greater than the one band form (P < 0.001).

Table 4.5 Anterior talofibular ligament (ATFL) width in the one, two and three band forms.

		N	Mean (mm)	P Value
ATFL Width (proximal)	One band	10	5.61 ± 1.51	0.037
	Two bands	40	5.26 ± 1.38	
	Three bands	13	4.18 ± 1.63	
ATFL Width (middle)	One band	10	6.02 ± 1.64	0.001
	Two bands	39	4.65 ± 1.12	
	Three bands	13	3.91 ± 1.42	
ATFL total width (proximal)	One band	11	5.1 ± 2.22	< 0.001
	Two bands	40	9.24 ± 1.89	
	Three bands	13	9.81 ± 2.32	
ATFL total width (middle)	One band	10	6.02 ± 1.64	< 0.001
	Two bands	39	8.24 ± 1.71	
	Three bands	13	8.94 ± 1.76	
ATFL total width (distal)	One band	10	5.02 ± 1.89	< 0.001
	Two bands	39	7.27 ± 1.69	
	Three bands	13	8.74 ± 1.56	

Table 4.6 Significant correlations between anterior talofibular ligament (ATFL) dimensions and different parameters: IATFL, inferior anterior talofibular ligament; MATFL, middle anterior talofibular ligament.

	Correlation with	N	correlation coefficient (r)	r^2	P Value
ATFL Length	ATFL Width (middle)	59	0.373	0.14	0.004
	ATFL Thickness	50	0.379	0.14	0.007
IATFL Length	IATFL Width (Proximal)	44	0.489	0.24	0.001
	IATFL Width (middle)	45	0.322	0.10	0.031
	IATFL Thickness	38	0.502	0.25	0.001
MATFL Length	Foot Length	10	0.675	0.46	0.032
ATFL Width (proximal)	1st metatarsal Length	58	0.311	0.10	0.018
MATFL Width (proximal)	Foot Length	11	- 0.657	0.43	0.028
ATFL total width (proximal)	Age	68	- 0.305	0.09	0.011
	Foot Length	62	0.315	0.10	0.013
ATFL total width (middle)	1st metatarsal Length	57	0.344	0.12	0.009
ATFL total width (distal)	Foot Length	62	0.395	0.16	0.003
	1st metatarsal Length	57	0.378	0.14	0.004

The single band form had a middle width of 6.02 ± 1.64 mm being significantly (P = 0.001) greater than the superior band in the two (4.65 ± 1.12 mm) and three (3.91 ± 1.41 mm) band forms. The middle width of the IATFL in the two band form (3.78 ± 1.25 mm) was not different from that in the three band form (3.14 ± 1.35 mm). The single band ATFL had a thickness of 0.73 ± 0.34 mm which did not differ from the superior band in the two (1.02 ± 0.34) and three (0.84 ± 0.32 mm) band forms: the thickness in the two band (0.55 ± 0.22 mm) and three band (0.63 ± 0.34 mm) forms did not differ. As shown in Table 4.6, ATFL length was correlated with its mid-width and thickness, while ATFL proximal width was correlated with 1st metatarsal length. There were also correlations between IATFL length and its proximal and mid-width as well as its thickness. MATFL length was only correlated with foot length, while a correlation between foot length and both the total proximal and distal widths, and between 1st metatarsal length and total middle width.

4.3.6 Change in Anterior Talofibular Ligament (ATFL) Length

There were significant differences in ATFL length (Figure 4.11) in dorsiflexion (18.01 ± 2.98 mm), plantarflexion (20.35 ± 3.01 mm) and inversion (20.1 ± 2.93 mm) compared to its length in neutral (18.92 mm ± 3.09) ($P < 0.001$); a difference in eversion (18.03 ± 3.26 mm) was also found ($P = 0.001$). In addition, significant differences between the length in dorsiflexion and plantarflexion ($P < 0.001$) and between inversion and eversion ($P < 0.001$) were observed. This suggests that ATFL length was significantly taut and stretched in plantarflexion and inversion and shorter in dorsiflexion and eversion. ATFL length in neutral ($r = -0.316$, $r^2 = 0.1$, $P = 0.024$), inversion ($r = -0.284$, $r^2 = 0.08$, $P = 0.045$) and eversion ($r = -0.322$, $r^2 = 0.1$, $P = 0.024$) were negatively correlated with maximum dorsiflexion PROM. However, other ATFL lengths in all joint positions were not correlated with their PROMs.

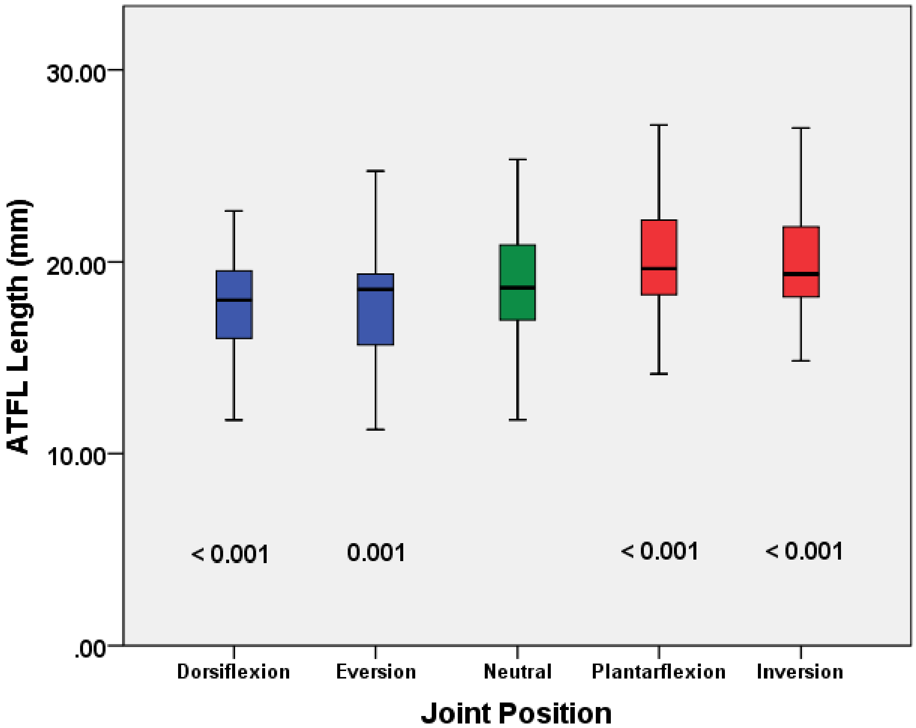

Figure 4.11 Change in the ATFL length in different joint positions.

There were no significant differences between IATFL length in neutral (15.64 ± 3.22 mm), dorsiflexion (15.5 ± 3.6 mm), plantarflexion (15.7 ± 3.59 mm), inversion (15.45 ± 3.74 mm) or eversion (15.48 ± 4.04 mm). In addition, the length in dorsiflexion was no different from that in plantarflexion, while the length in inversion was not different from that in eversion. IATFL lengths in the different joint positions were not correlated with their PROMs.

MATFL length in dorsiflexion (17.65 ± 2.71 mm), plantarflexion (18.78 ± 3.4 mm), inversion (18.7 ± 3.55 mm) and eversion (17.82 ± 3.05 mm) were similar compared to the length in neutral (17.42 ± 4.39 mm). Additionally, there was no difference between in lengths between dorsiflexion and plantarflexion, or between inversion and eversion. Moreover, MATFL change in length in different joint positions was not correlated with their maximum PROMs.

4.3.7 ATFL Bony Attachment Lengths

Table 4.7 shows the ATFL bony attachment lengths, as well as the free length of the ligament. As can be seen 24.9% of ATFL length was attached proximally (proximal bony attachment; PBA) to the fibula, while 59.9% and 15.2% of the ligament comprised the free length (no bony attachment; NBA) and the length of the distal bony attachment (DBA) to the talus respectively. The IATFL PBA, NBA and DBA values were 22.26%, 58.5% and 18.92% of the total IATFL length respectively, while for the MATFL these values were 22.74%, 64.19% and 13.06%. There was no difference in the ATFL bands PBA, NBA and DBA between males and females or between right and left sides. MATFL NBA was the only parameter that was correlated with foot length ($r = 0.714$, $r^2 = 0.51$, $P = 0.046$). ATFL DBA was also correlated with the ATFL total distal width ($r = -0.389$, $r^2 = 0.15$, $P = 0.011$); while the IATFL NBA was correlated with the ATFL total middle width ($r = 0.446$, $r^2 = 0.2$, $P = 0.005$).

Table 4.7 Proximal bony attachment (PBA), no bony attachment (NBA) and dorsal bony attachment (DBA) lengths of the different bands of the anterior talofibular ligament (ATFL): IATFL, inferior talofibular ligament; MATFL, middle talofibular ligament.

Band	Length	N	Mean (mm)	% of the total length (PF)
ATFL	**PBA**	43	5.08 ± 3.31	24.90%
	NBA	43	12.22 ± 3.57	59.90%
	DBA	43	3.1 ± 1.98	15.20%
IATFL	**PBA**	39	3.6 ± 2.63	22.26%
	NBA	39	9.46 ± 3.33	58.50%
	DBA	40	3.06 ± 2.1	18.92%
MATFL	**PBA**	8	4.23 ± 2.54	22.74%
	NBA	8	11.94 ± 3.25	64.19%
	DBA	8	2.43 ± 1.24	13.06%

4.3.8 Relations to Other Ligaments

In the one band form of the ATFL, it was separated from the CFL proximally 4.32 ± 1.23 mm distal to the ATFL proximal attachment. In the two band form its proximal fibres attached with the IATFL in 86.7%, separating 5.42 ± 2.76 mm distal to the ATFL proximal attachment: of these 23.08% were also free a further 1.5 ± 0.6 mm proximally above the IATFL proximal attachment. Distally, 54.3% of ATFLs had an attachment with the IATFL which separated 6.07 ± 2.36 mm proximal to the ATFL distal attachment: in 78.9% the ATFL extended 3.14 ± 1.9 mm distally from the IATFL distal attachment. In the two and three band forms the IATFL separated from the CFL 3.18 ± 1.66 mm distal to the IATFL proximal attachment: in one specimen the IATFL extended 0.67 mm proximally. In addition, the IATFL had a distal attachment to the LTCL in 95.24% of specimens, separating from it 6.68 ± 3.25 mm proximal to the IATFL distal attachment: 45% extended a further 2.43 ± 1.79 mm distally from the LTCL.

In the three band form the ATFL had a proximal attachment to the MATFL in 95.24%, separating 6.7 ± 3.49 mm distal to the ATFL proximal attachment: in one specimen it extended 2.33 mm proximally. The ATFL had a distal attachment to the MATFL in all specimens, separating 5.56 ± 2.42 mm proximal to the ATFL distal attachment: 77.78% extended a further 3.33 ± 1.81 mm distally. Moreover, the MATFL separated proximally from the IATFL 7.91 ± 1.28 mm distal to the MATFL proximal attachment, with 25% extending a further 1.46 ± 0.02 mm proximally. In addition, the MATFL had a distal attachment with the IATFL, separating 4.75 ± 2.34 mm proximal to the MATFL distal attachment: 66.7% extended a further 2.39 ± 2.58 mm distally.

4.3.9 ATFL Deep Additional Band

In one male, right sided specimen the ATFL consisted of three bands: superior, inferior and a band deep to the ATFL (Figure 4.12). In this case the ligament had some fibres attached to the ATFL and IATFL proximally and crossed medially being orientated anterosuperiorly in all joint positions. It crossed to insert to the talus 5.91 mm anterior to the ALML and posterior to the ATFL (superficial) insertion, which was 6.32 mm anterior to the ALML. This band had a length and thickness of 15.29 mm and 0.81 mm respectively.

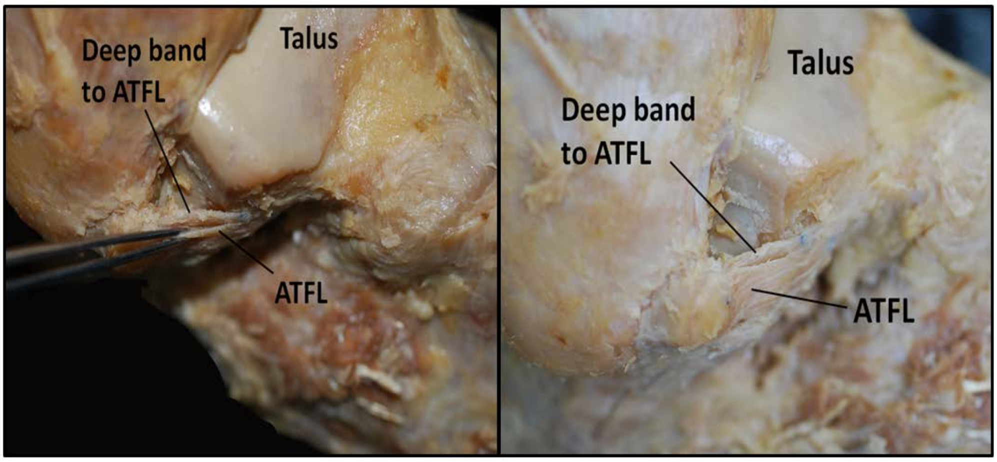

Figure 4.12 Deep band to the anterior talofibular ligament (ATFL).

4.4 Calcaneofibular Ligament (CFL)

4.4.1 Proximal Attachment of the Calcaneofibular Ligament (CFL)

The calcaneofibular ligament (CFL) attached proximally to the inferior part of the anterior border of the lateral malleolus of the fibula (Figure 4.13), originating anterior to the lateral malleolar tip (82.1%), extending to the tip (16.1%) and medial to the tip (1.8%). The CFL origin did not differ in relation to age, foot length, 1st metatarsal length, angle between the ATFL and CFL or the CFL PBA. However, there was a difference in 1st metatarsal length in relation to the CFL origin (P = 0.047). Feet with the mean 1st metatarsal length of 64.38 mm, 60.69 mm and 65.51 mm had their CFL attached proximally anterior to the lateral malleolar tip, extended to the tip and medial to the tip respectively. In addition, there was a difference in CFL length according to its origin (P = 0.044); 31.5 mm, 26.87 mm and 27.12 mm were the CFL lengths in neutral when it had a proximal attachment anterior to the lateral malleolar tip, extending to the tip and medial to the tip respectively.

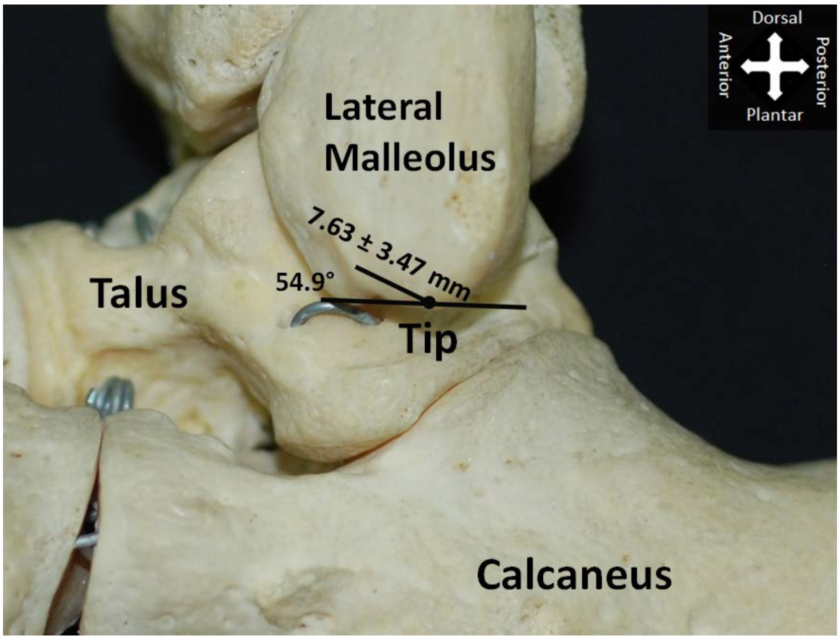

Figure 4.13 Proximal attachment of the calcaneofibular ligament; distance and angle between the mid proximal attachment and the lateral malleolar tip.

The distance and angle between the mid proximal attachment of the CFL and the lateral malleolar tip were 7.63 ± 3.47 mm and 55° ± 21° respectively (Figure 4.13). No difference in distance or angle was observed between gender, foot side or origin in relation to the lateral malleolar tip. Analysis showed no correlation between the angle of the CFL proximal attachment to the lateral malleolar tip and age, foot length, 1st metatarsal length, CFL length, proximal width, angle between the ATFL and CFL, CFL PBA or to the distance of the proximal attachment to the tip. The distance between the lateral malleolar tip and the CFL origin was correlated with CFL length ($r = 0.540$, $r^2 = 0.29$, $P < 0.001$), as well as between the distance of the proximal attachment to the tip and the CFL PBA ($r = 0.455$, $r^2 = 0.21$, $P = 0.008$). No other correlations were observed.

4.4.2 Distal Attachment of the Calcaneofibular Ligament (CFL)

The CFL inserted distally into the posterior part of the lateral surface of the calcaneus (Figure 4.14), being posterosuperior (81.4%) or posteroinferior (18.6%) to the fibular tubercle on its lateral surface. There was no difference in foot length, 1st metatarsal length, distal width, CFL DBA or the angle between ATFL and CFL in relation to the CFL distal insertion point (posterosuperior or posteroinferior). However, CFL length was significantly different in relation to the CFL distal insertion, being 29.53 mm and 34.21 mm when attached posterosuperior or posteroinferior to the fibular tubercle respectively. In addition, a difference in mean age was found between the posterosuperior (82.23 years old) and posteroinferior (88.82 years old) insertions.

The distance and angle between the mid distal attachment of the CFL and the fibular tubercle were 17.7 ± 4.48 mm and 10° ± 13° (range - 22° to 31°) (Figure 4.14), with no difference between right and left feet. However, a significant difference in distance was found between males and females (P = 0.019), with males showing a mean distance of 19.4 ± 5.32 mm and females 16.66 ± 3.58 mm. Additionally, the angle was different between genders (P = 0.025), with that in males and females being 4° ± 15° and 13° ± 11° respectively.

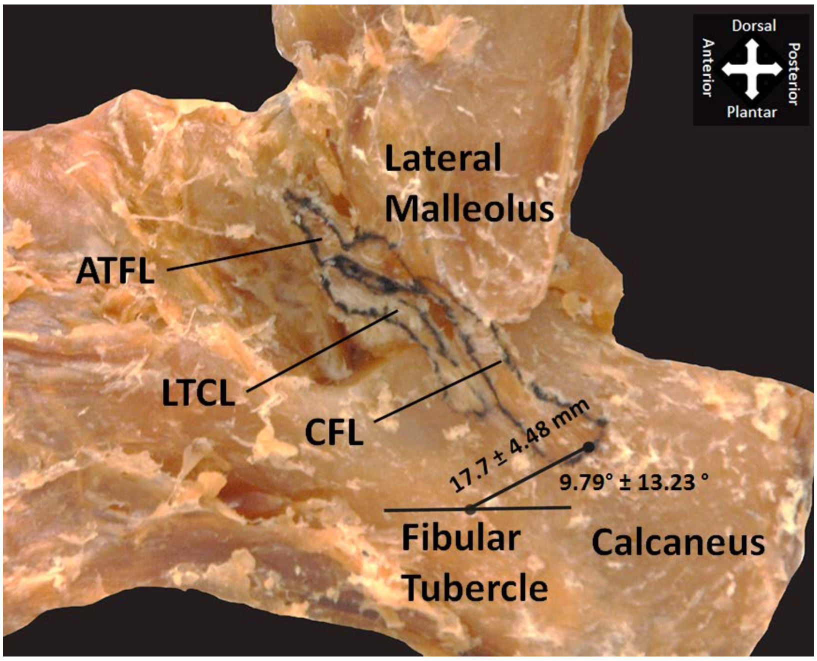

Figure 4.14 Distal attachment of the calcaneofibular ligament (CFL) showing the distance and angle between the mid distal attachment and the calcaneal fibular tubercle: ATFL, anterior talofibular ligament; LTCL, lateral talocalcaneal ligament.

The CFL mid distal attachment distance to the fibular tubercle was correlated with foot length (r = 0.278, r^2 = 0.077, P = 0.035), CFL length in neutral (r = 0.377, r^2 = 0.14, P = 0.004), CFL DBA (r = 0.358, r^2 = 0.13, P = 0.02) and the angle of the distal attachment to the fibular tubercle ($r = -0.319$, $r^2 = 0.1$, $P = 0.012$). The angle of the CFL distal attachment to the fibular tubercle was correlated with age ($r = -0.267$, $r^2 = 0.07$, $P = 0.038$), CFL length ($r = -0.509$, $r^2 = 0.26$, $P < 0.001$) and the CFL DBA ($r = 0.381$, $r^2 = 0.15$, $P = 0.013$).

4.4.3 Calcaneofibular Ligament (CFL) Orientation

The CFL crossed from the lateral malleolus medially to the calcaneus, being orientated posteroinferiorly in all specimens and all joint positions (Figures 4.15 and 4.16).

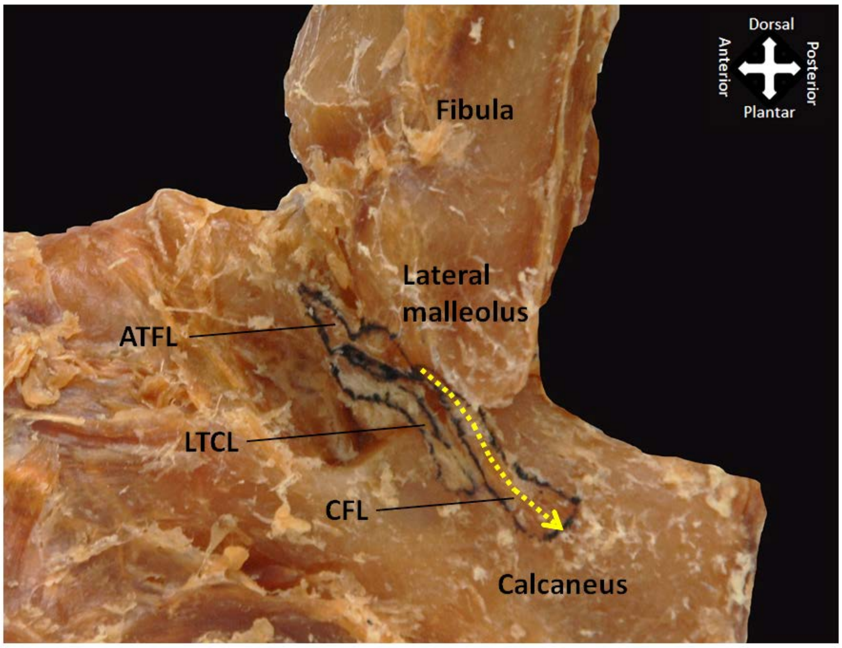

Figure 4.15 Calcaneofibular ligament (CFL) orientation (yellow dotted arrow) in neutral position: ATFL, anterior talofibular ligament; LTCL, lateral talocalcaneal ligament.

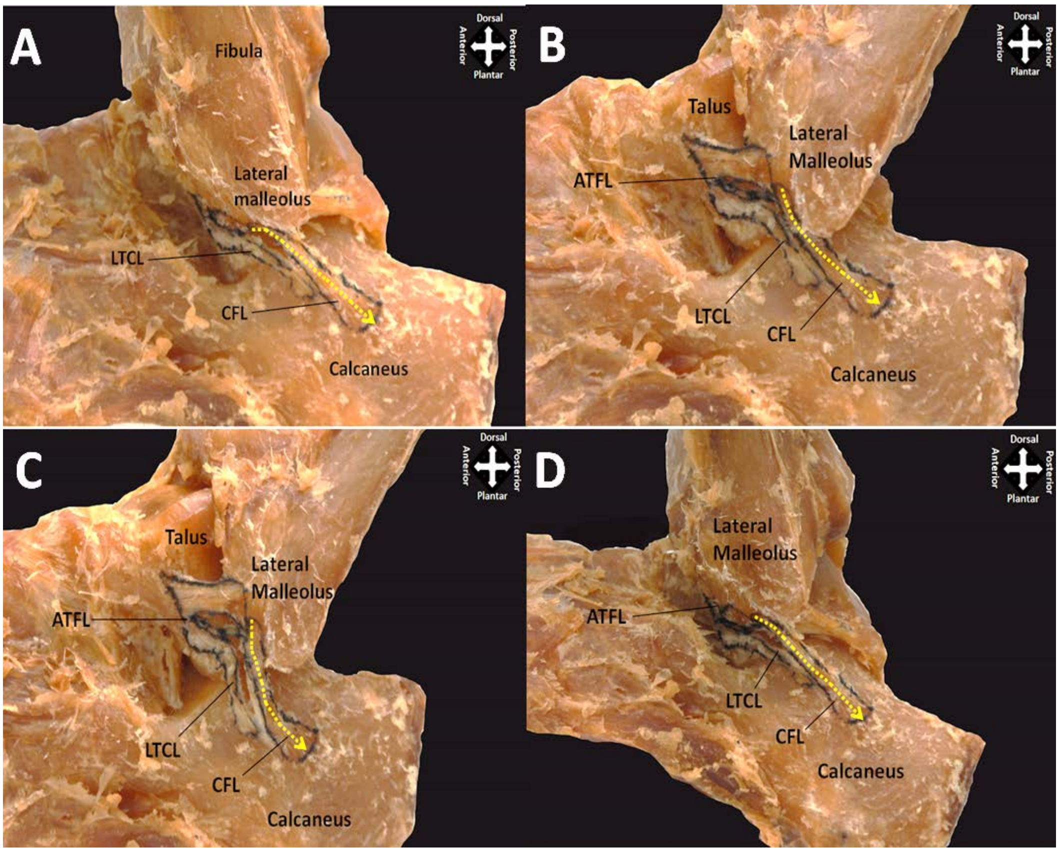

Figure 4.16 Calcaneofibular ligament (CFL) orientation (yellow dotted arrows) in different joint positions: A, Dorsiflexion; B, Plantarflexion; C, Inversion; D, Eversion; ATFL, anterior talofibular ligament; LTCL, lateral talocalcaneal ligament.

4.4.4 Calcaneofibular (CFL) Dimensions

The mean CFL length, mid-width and thickness were 30.18 ± 5.03 mm, 4.19 ± 1.55 mm and 1.40 ± 0.48 mm respectively (Table 4.8). There was no difference in these parameters between right and left sides; however, there was difference in distal width ($P = 0.004$), with the right and left sides being 6.26 ± 1.44 mm and 7.51 ± 1.86 mm respectively. The proximal width, mid-width, distal width and thickness showed no difference between males and females. However, CFL length was different between males and females ($P < 0.001$), being in males 33.06 ± 5.19 mm and females 28.16 ± 3.84 mm. There were no differences between the mid and proximal widths; however, a significant difference between the mid and distal widths was observed (P < 0.001) as well as between the proximal and distal widths (P < 0.001). This suggests that the distal width was significantly wider than the proximal and mid widths.

Table 4.8 Calcaneofibular ligament (CFL) dimensions.

CFL Dimension		N	Mean ± SD (mm)
CFL Length	**Neutral**	63	30.18 ± 5.03
CFL Width	**Proximal**	62	4.3 ± 1.4
	Middle	63	4.19 ± 1.55
	Distal	65	6.89 ± 1.77
CFL Thickness	**Middle**	52	1.40 ± 0.48

CFL length was correlated with foot length (r = 0.352, r^2 = 0.12, P = 0.007) and 1st metatarsal length (r = 0.491, r^2 = 0.24, P < 0.001); CFL proximal width was correlated with both the mid (r = 0.326, r^2 = 0.11, P = 0.01) and distal (r = 0.404, r^2 = 0.16, P = 0.001) width. The mid width was correlated with distal width only (r = 0.534, r^2 = 0.29, P < 0.001), age was correlated with distal width (r = 0.304, r^2 = 0.09, P = 0.014).

4.4.5 Change in CFL Length

The CFL (Figure 4.17) significantly changed in length in dorsiflexion (P = 0.002), plantarflexion (P < 0.001) and inversion (P = 0.006) compared to neutral, while in eversion there was no difference (P = 0.212). Moreover, there were significant differences between CFL length in dorsiflexion and plantarflexion (P < 0.001), and between inversion and eversion (P < 0.001).

This suggests that the CFL resists dorsiflexion and eversion and is relaxed in plantarflexion and inversion. PROMs were not correlated with CFL length in neutral (30.62 ± 5.14 mm), dorsiflexion (31.23 ± 5.16 mm), plantarflexion (29.05 ± 5.31 mm), inversion (29.65 ± 4.45 mm) or eversion (30.85 ± 5.06 mm).

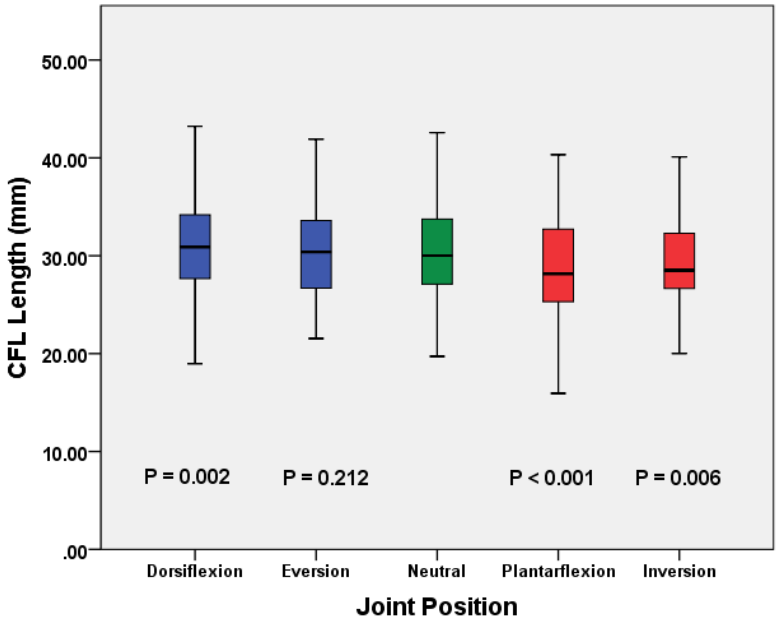

Figure 4.17 Change in calcaneofibular ligament (CFL) length in different joint positions.

4.4.6 CFL Bony Attachment Lengths

10.45% of the CFL length had a proximal bony attachment to the lateral malleolus, while 28.75% had a distal bony attachment (DBA) to the calcaneus; the free length or no bony attachment length (NBA) was therefore 60.80% of the total ligament length (Table 4.9). The CFL NBA and DBA showed no difference between right and left sides; however, there was a significant difference in CFL PBA between right and left sides (P = 0.031): the right and left sides being 4.03 ± 2.44 mm and 2.34 ± 2.44 mm respectively. There was no difference in the

PBA and DBA lengths between males and females; however, a difference in NBA length was observed ($P = 0.005$) between males (20.3 ± 4.48 mm) and females (16.75 ± 3.18 mm). CFL PBA was correlated with both CFL length ($r = 0.310$, $r^2 = 0.1$, $P = 0.049$) and CFL origin distance to the lateral malleolar tip ($r = 0.455$, $r^2 = 0.21$, $P = 0.008$). CFL NBA correlated with foot length ($r = 0.395$, $r^2 = 0.16$, $P = 0.012$), 1st metatarsal length ($r = 0.508$, $r^2 = 0.26$, $P = 0.001$) and CFL length ($r = 0.708$ $r^2 = 0.5$, $P < 0.001$), CFL DBA was correlated with CFL length ($r = 0.435$, $r^2 = 0.19$, $P = 0.004$).

Table 4.9 Calcaneofibular ligament (CFL) bony attachment lengths: PBA, proximal bony attachment; NBA, no bony attachment; DBA, distal bony attachment; PF, plantarflexion.

	N	Mean (mm)	% of the total length (PF)
CFL PBA	42	3.11 ± 2.56	10.45%
CFL NBA	42	18.1 ± 4.07	60.80%
CFL DBA	42	8.56 ± 2.54	28.75%

4.4.7 Relations to Different Ligaments and Bands

Proximally the CFL separated from the IATFL 3.91 ± 1.74 mm distal to the CFL proximal attachment. In 22.22% of specimens, it separated from the LTCL 12.63 ± 6.72 mm distal to the CFL proximal attachment, with 7.63 ± 4.47 mm being free proximally. In addition, in 72.73% of specimens the CFL separated distally from the LTCL 13.66 ± 6.45 mm proximal to the CFL distal attachment, with 5.93 ± 4.43 mm being free distally.

In some specimens, some fibre fasciculation was seen superficially, but it was not separated into independent bands. In addition, there was an additional CFL band in two specimens. In one the additional band was located anterior to the CFL (Figure 4.18), originating proximally from the anterior border of the lateral malleolus 6.64 mm from the tip with an angle of 64°. Distally it inserted into the lateral surface of the calcaneus, anterior border of the CFL posterosuperior to the fibular tubercle of the calcaneus: the distance and angle between the mid distal attachment and fibular tubercle were 13.09 mm and 46° respectively. It had a length of 23.95 mm in neutral, 25.91 mm in dorsiflexion, 19.11 mm in plantarflexion, 22.41 mm in inversion and 22.14 mm in eversion. Its proximal, middle and distal widths were 4.21 mm, 2.32 mm and 1.38 mm respectively, while its thickness was 1.39 mm.

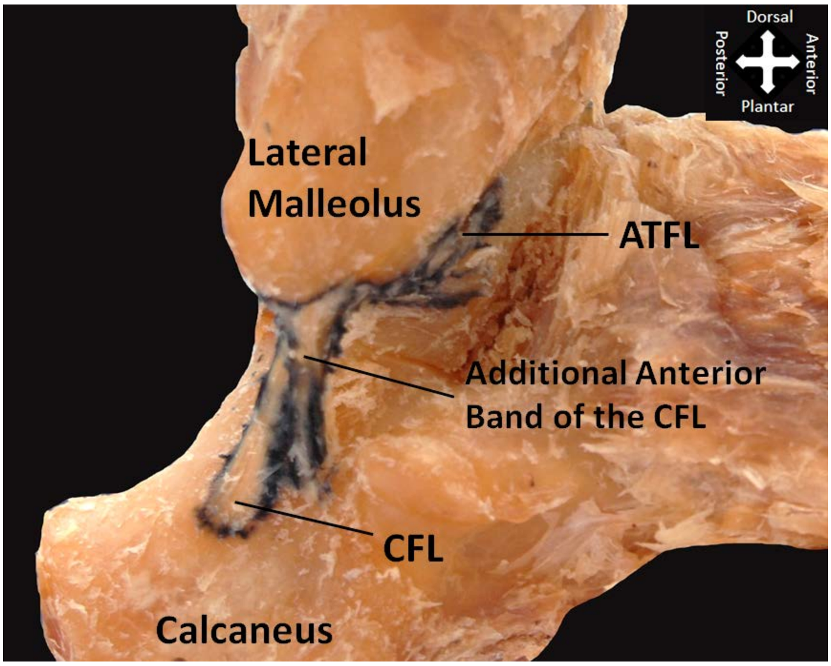

Figure 4.18 Additional band anterior to the calcaneofibular ligament (CFL): ATFL, anterior talofibular ligament.

The second specimen had an additional band posterior to the CFL (Figure 4.19). Its proximal attachment was posterior to the lateral malleolar tip: distance and angle to the tip were 2.92 mm and 65°. The band inserted distally to the calcaneal lateral surface, posterior aspect of the CFL posterosuperior to the fibular tubercle: distance and angle between the distal attachment and fibular tubercle were 21.42 mm and 24° respectively. The band had a length of 22.21 mm in neutral, 25 mm in dorsiflexion, 17.59 mm in plantarflexion, 18.49 mm in inversion and 24.87 mm in eversion. The proximal, middle and distal widths were 1.83 mm, 2.33 mm and 1.96 mm respectively and its thickness 0.77 mm.

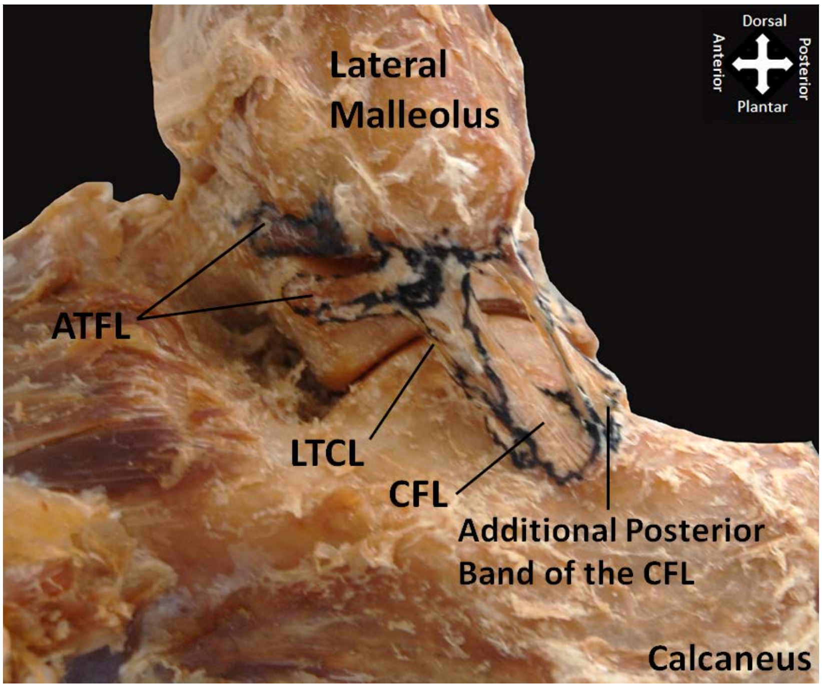

Figure 4.19 Additional band posterior to the calcaneofibular ligament (CFL): LTCL, lateral talocalcaneal ligament.

4.5 Posterior Talofibular Ligament (PTFL)

4.5.1 Proximal Attachment of the Posterior Talofibular Ligament (PTFL)

The PTFL originated proximally from the malleolar fossa of the lateral malleolus of the fibula (Figure 4.20), with the mean distance between its mid proximal attachment and the lateral malleolar tip 9.75 ± 1.61 mm. There was a significant difference in the distance between the PTFL origin and lateral malleolar tip between genders, with the distance in males being 10.52 ± 1.72 mm and in females 9.2 ± 1.3 mm. The distance was not correlated with age, foot length, 1st metatarsal length, proximal width or the PTFL PBA.

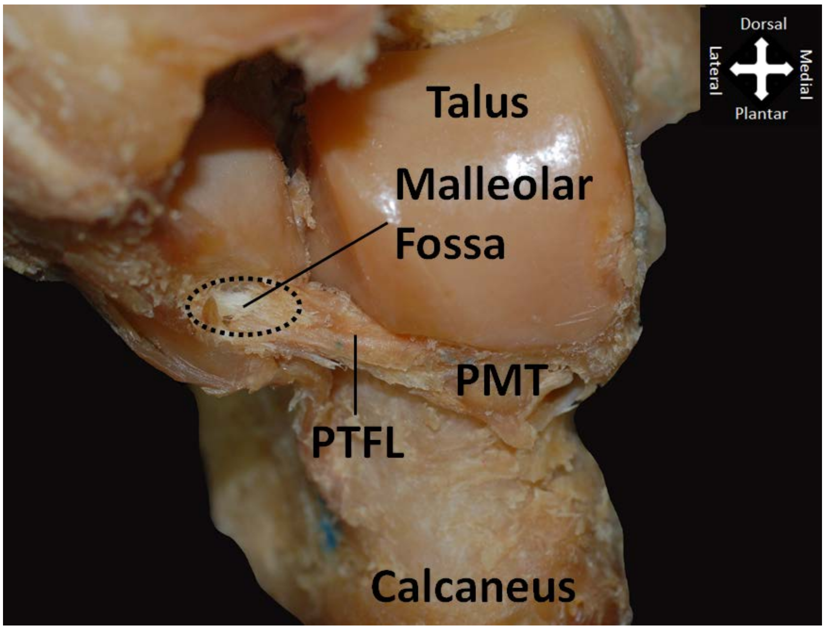

Figure 4.20 Proximal attachment of the posterior talofibular ligament (PTFL) (dotted circle); PMT, posteromedial tubercle of the talus.

4.5.2 Distal Attachment of the PTFL

The PTFL crossed medially from the malleolar fossa posteroinferiorly (Figure 4.21) to insert distally along the posterolateral surface of the talus (Figure 4.22), extending as far as the lateral and superior (76.8%) or lateral (23.2%) aspects of the posterolateral tubercle (PLT) of the talus. No differences in age, foot length, PTFL length, proximal width or PTFL PBA in relation to the PTFL distal attachment were identified. However, a significant difference in the 1st metatarsal length was found in relation to the PTFL insertion (P = 0.043), with the mean length in specimens attaching to the lateral and superior and lateral parts of the posterolateral tubercle being 63.96 ± 4.65 mm and 60.89 ± 3.94 mm respectively.

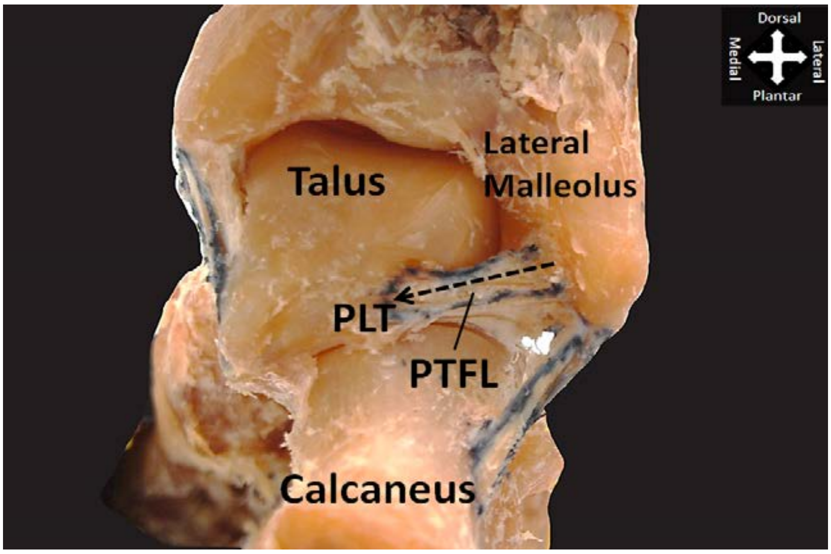

Figure 4.21 Posterior talofibular ligament (PTFL) crossing medially and posteroinferiorly (black dotted arrow): PLT, posterolateral tubercle of the talus.

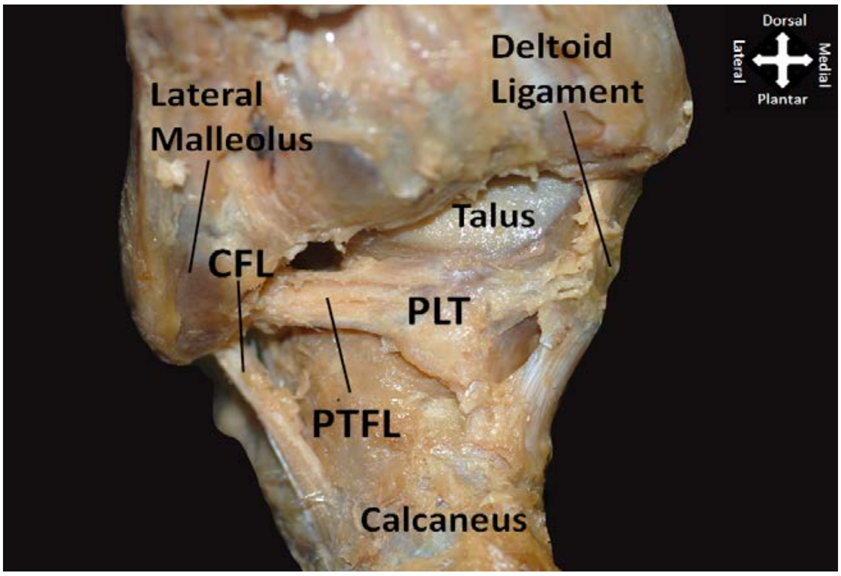

Figure 4.22 Distal attachment of the posterior talofibular ligament (PTFL) to the lateral and superior aspects of the posterolateral tubercle (PLT) of the talus.

4.5.3 Posterior Talofibular (PTFL) Dimensions

The PTFL had a mean length, mid-width and thickness of 24.03 mm, 5.52 mm and 2.06 mm respectively (Table 4.10). The distal width was similar in males and females; however, there was a significant difference in PTFL length ($P < 0.001$), proximal width ($P = 0.009$), mid-width ($P = 0.001$) and thickness ($P = 0.016$) between genders (Table 4.11). These results indicate that males have a longer PTFL with it being wider proximally and at its mid width, as well as being thicker compared to females. There was no difference in PTFL dimensions between the right and left sides. Compared to the mid-width, there was a significant difference with respect to the proximal ($P < 0.001$) and distal widths ($P = 0.007$); however, there was no difference between the proximal and distal widths. This suggests that the proximal and distal widths are significantly wider than at the middle. PTFL length was correlated with foot length ($r = 0.575$, $r^2 =$

0.33, P <0.001), 1st metatarsal length (r = 0.636, r^2 = 0.4, P < 0.001) and PTFL proximal width (r = 0.438, r^2 = 0.19, P = 0.001). PTFL was correlated with 1st metatarsal length (r = 0.332, r^2 = 0.11, P = 0.01), PTFL length (r = 0.438, r^2 = 0.19, P = 0.001) and mid-width (r = 0.510, r^2 = 0.26, P <0.001).

Table 4.10 Posterior talofibular ligament (PTFL) dimensions.

		N	Mean ± SD (mm)
PTFL Length	**Total length**	59	24.03 ± 3.55
PTFL Width	**Proximal**	59	7.1 ± 1.72
	Middle	60	5.52 ± 1.64
	Distal	62	6.48 ± 2.05
PTFL Thickness	**Middle**	58	2.06 ± 0.62

Table 4.11 Differences in posterior talofibular ligament (PTFL) length, proximal width, distal width and thickness between males and females.

PTFL dimension	Sig.	Gender	N	Mean ± SD (mm)
Length	< 0.001	Male	24	26.44 ± 2.76
		Female	35	22.38 ± 3.08
Proximal width	0.009	Male	23	7.82 ± 1.8
		Female	36	6.64 ± 1.52
Mid-width	0.001	Male	24	6.34 ± 1.62
		Female	36	4.97 ± 1.43
Thickness	0.016	Male	21	2.32 ± 0.66
		Female	37	1.92 ± 0.55

4.5.4 Change in Posterior Talofibular Ligament (PTFL) Length

The true length of the PTFL (23.68 ± 3.53 mm) was significantly different (P < 0.001) compared to that taken initially before dislocating the ankle joint in neutral (20.4 ± 2.93 mm), dorsiflexion (21.16 ± 2.74 mm) and eversion (21.04 ± 2.93 mm): there was a significant difference between neutral and dorsiflexion positions ($P < 0.001$). The PTFL length in neutral was negatively correlated with isolated inversion PROM ($r = -0.351$, $r^2 = 0.12$, $P = 0.021$) and isolated eversion PROM ($r = -0.321$, $r^2 = 0.1$, $P = 0.036$). In addition, there were correlations between PTFL length in eversion and isolated inversion PROM ($r = -0.437$, $r^2 = 0.19$, $P = 0.006$) and isolated eversion PROM ($r = -0.409$, $r^2 = 0.17$, $P = 0.011$).

4.5.5 PTFL Bony Attachment Lengths

Of the PTFL total length 15.13% and 58.04% were attached to the malleolar fossa proximally and the talus distally, leaving the free length of the ligament at 26.82% (NBA) (Table 4.12). There was no difference in PTFL PBA and NBA between males and females; however there was a significant difference in the PTFL DBA between genders ($P = 0.012$), with males and females having a PTFL DBA of 15.79 ± 3.45 mm and 12.8 ± 3.94 mm respectively. There was no difference in PTFL PBA, NBA and DBA between right and left sides. PTFL NBA was correlated with PTFL DBA only ($r = -0.427$, $r^2 = 0.18$, $P = 0.003$), while PTFL DBA was correlated with foot length ($r = 0.321$, $r^2 = 0.1$, $P = 0.033$), 1st metatarsal length ($r = 0.402$, $r^2 = 0.16$, $P = 0.006$), PTFL length ($r = 0.742$, $r^2 = 0.55$, $P < 0.001$) and the PTFL NBA ($r = -0.427$, $r^2 = 0.18$, $P = 0.003$).

Table 4.12 Posterior talofibular ligament (PTFL) bony attachment lengths: PBA, proximal bony attachment; NBA, no bony attachment; DBA, distal bony attachment.

	N	Mean ±SD (mm)	% total length
PTFL PBA	45	3.65 ± 2.31	15.13%
PTFL NBA	45	6.47 ± 2.25	26.82%
PTFL DBA	45	14 ± 4.00	58.04%

4.6 Medial Collateral ligament (MCL; deltoid)

The deltoid ligament (Figure 4.23) was a complex structure that originated from the medial malleolus of the tibia and inserted widely into the navicular, spring (talocalcaneonavicular) ligament, calcaneus and talus. The ankle joint capsule was also observed to be attached to the anterior and posterior aspects of the MCL. The shape of the deltoid ligament was complex and irregular, but with the most resembling a trapezoidal shape (Figure 4.23).

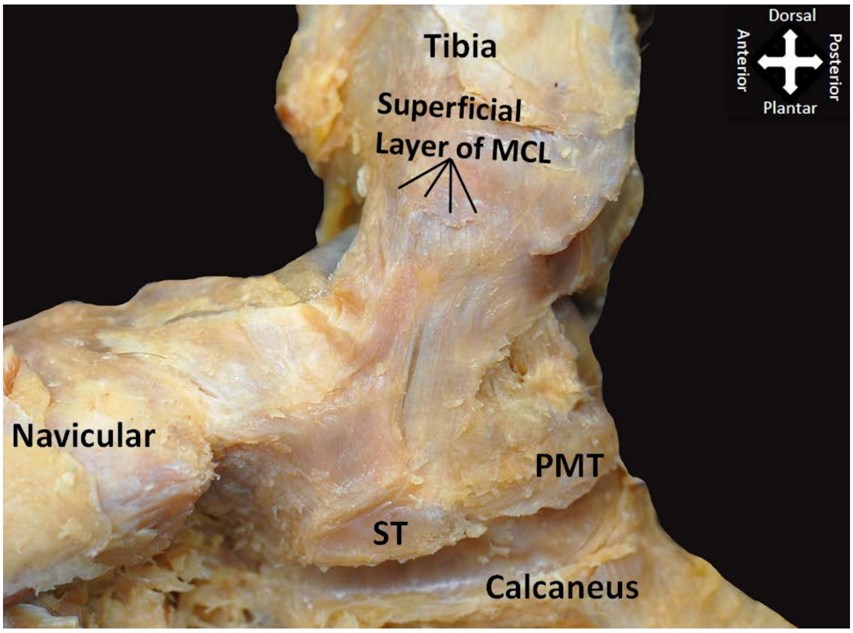

Figure 4.23 Superficial layer of the medial collateral ligament (MCL); ST, sustentaculum tali; PMT, posteromedial tubercle of the talus.

The ligamentous complex consisted of two layers: superficial (Figure 4.23) and deep (Figure 4.24), between which adipose tissue was found, as well as a few small fibres passing between the layers. The superficial layer always covered the anterior tibiotalar part (ATTL) of the deep layer; while the posterior tibiotalar ligament (PTTL) had a variable covering (discussed in the PTTL part of this chapter). The order of the superficial components from anterior to posterior was tibionavicular (TNL), tibiospring (TSL), tibiocalcaneal (TCL) and superficial tibiotalar ligaments (STT), while the deep component consisted of the anterior tibiotalar (ATTL) anteriorly and the posterior tibiotalar (PTTL) posteriorly.

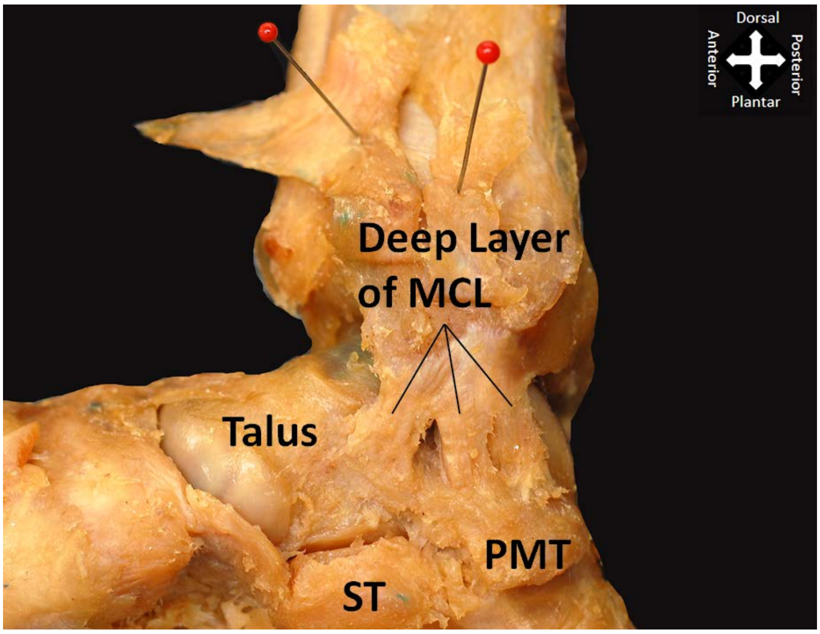

Figure 4.24 Deep layer of the medial collateral ligament (MCL) after reflecting the superficial layer: ST, sustentaculum tali; PMT, posteromedial tubercle of the talus.

4.7 Tibionavicular Ligament (TNL)

The TNL (Figure 4.25) was observed in all specimens examined and was not covered by any other ligament in 67.3% of specimens; however its posterior aspect was partially covered by the TSL in 32.7% of specimens. In addition, the TNL was observed to be continuous with the deep fibres of the TSL in 86%, while in 14% it had some fibres separating it from the TSL. There was no difference between males and females or between right and left sides.

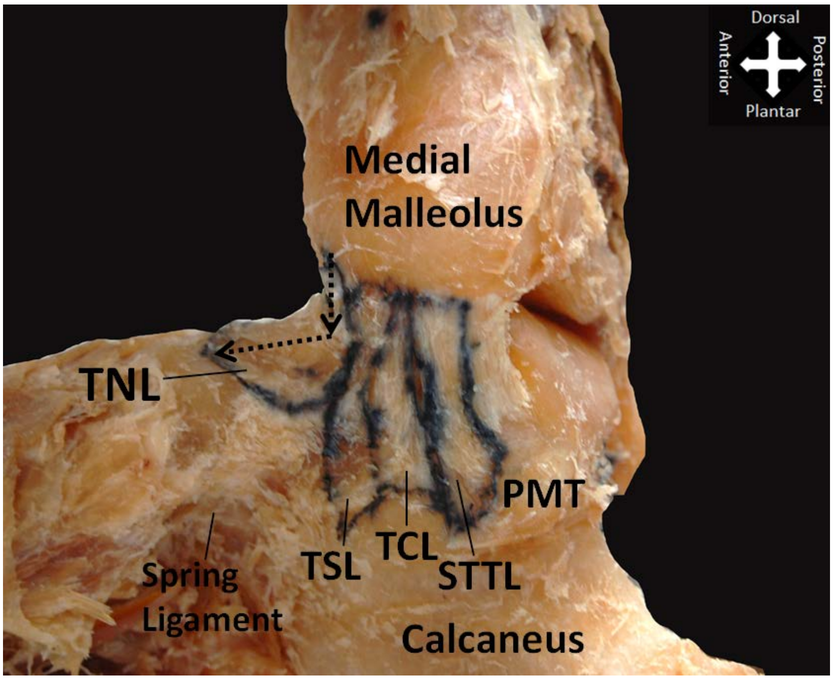

Figure 4.25 Tibionavicular ligament (TNL) in the neutral position: PMT, posteromedial tubercle of the talus; black dotted arrow shows the TNL orientation.

4.7.1 Proximal Attachment of the Tibionavicular Ligament (TNL)

The TNL attached proximally to the anterior border of the anterior colliculus of the medial malleolus in 94%, while in the remaining 6% it originated from the anterior border and medial surface of the anterior colliculus (Figure 4.26). There was no difference in the TNL proximal attachment between males and females or between right and left sides.

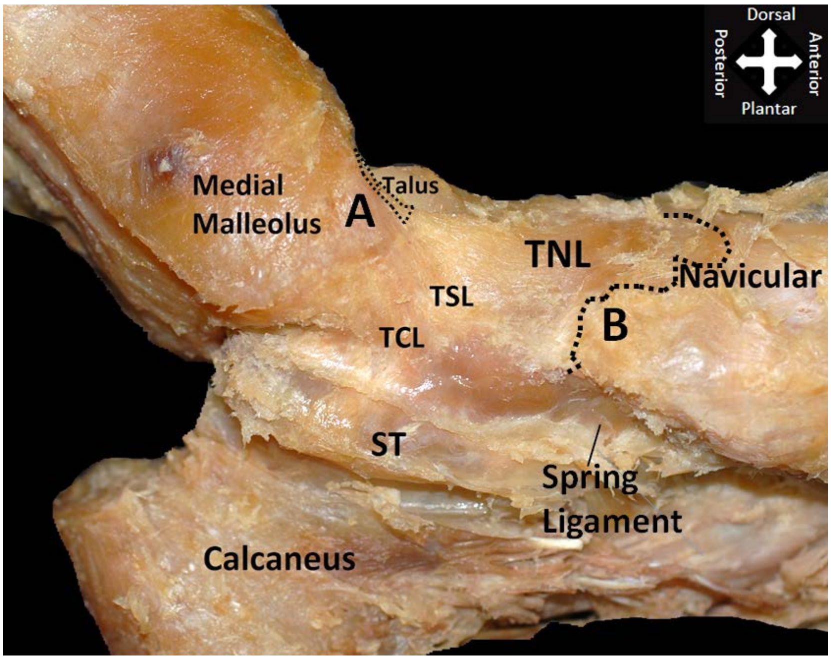

Figure 4.26 Proximal (A) and distal (B) attachment of the tibionavicular ligament (TNL): ST, sustentaculum tali; TCL, tibiocalcalcaneal ligament; TSL, tibiospring ligament.

4.7.2 Distal Attachment of the Tibionavicular Ligament (TNL)

The TNL crossed laterally initially anteroinferiorly and then anterosuperiorly in all joint positions to its distal attachment (Figures 4.26, 4.27, and 4.28). The wide insertion (Figure 4.26) was to the dorsomedial surface of the navicular, the talar medial surface as far as the neck, as well as to the fibrocartilaginous fibres that connected to the spring ligament in 88.3% of specimens, while in the remaining specimens (11.7%) it inserted to the dorsomedial surface of the navicular and the spring ligament connecting fibres. The TNL distal attachment did not differ between genders or foot side.

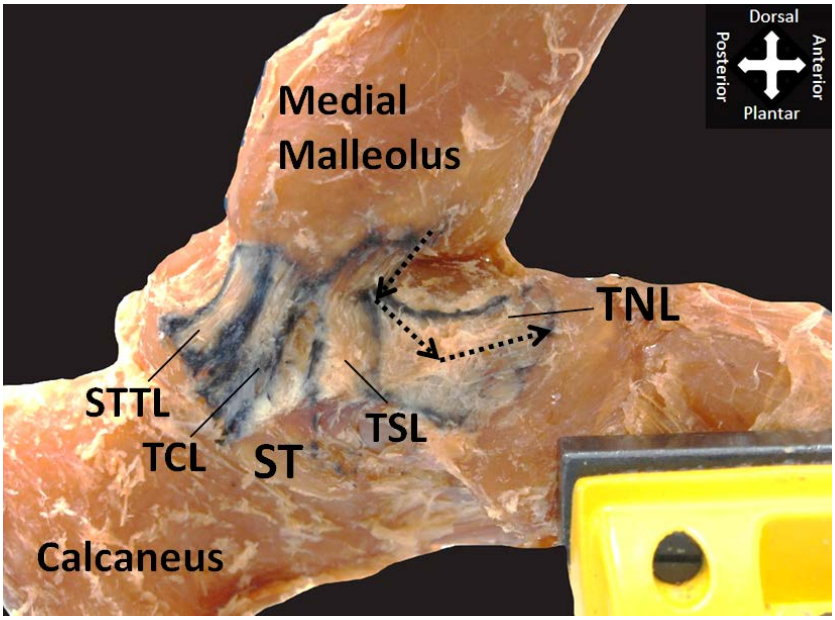

Figure 4.27 Tibionavicular ligament (TNL) orientation (black dotted arrows) in dorsiflexion: STTL, superficial tibiotalar ligament; TCL, tibiocalcaneal ligament; TSL, tibiospring ligament; ST, sustentaculum tali.

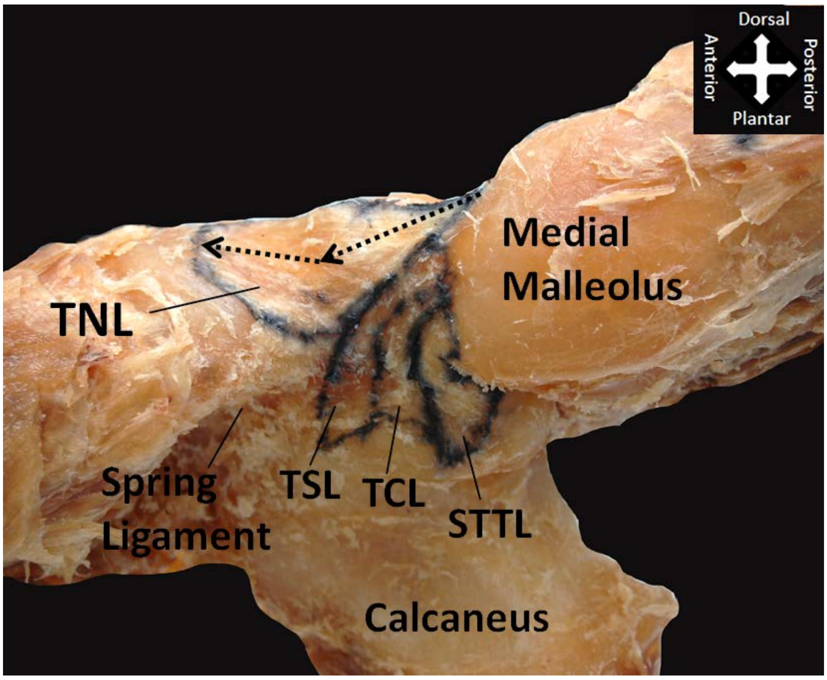

Figure 4.28 Tibionavicular ligament (TNL) orientation (black dotted arrows) in plantarflexion: STTL, superficial tibiotalar ligament; TSL, tibiospring ligament; TCL, tibiocalcaneal ligament.

4.7.3 Tibionavicular Ligament (TNL) Dimensions

The TNL had a length, mid-width and thickness of 34.16 ± 5.72 mm, 12.58 ± 3.06 mm and 0.62 ± 0.28 mm respectively (Table 4.13). There was no difference in proximal width, distal width and thickness between males and females; however, TNL length (P = 0.014) and mid-width (P = 0.026) were significantly different between genders. TNL length was 36.85 ± 6.75 mm in males and 32.15 ± 3.84 mm in females, while its mid-width was 13.93 ± 3.62 mm in males and 11.67 ± 2.26 mm in females. There was no difference in proximal width, distal width and thickness between right and left sides. However, there was a significant difference in TNL length (P = 0.021) and mid-width (P = 0.036) between foot side, with the mean length in right and left feet being 36.27 ± 5.76 mm and 32.25 ± 5.08 mm respectively. The mean mid-width was 13.54 ± 3.49 mm in right and 11.65 ± 2.29 mm in left feet.

Table 4.13 Tibionavicular ligament (TNL) length, width and thickness.

TNL Dimension		**N**	**Mean ± SD (mm)**
TNL Length	Neutral	42	34.16 ± 5.72
TNL Width	Proximal	58	4.8 ± 2.22
	Middle	45	12.58 ± 3.06
	Distal	61	9.5 ± 2.88
TNL Thickness	Middle	44	0.62 ± 0.28

Compared to TNL mid-width there was a significant difference in the proximal (P < 0.001) and distal (P < 0.001) widths; the proximal width was also significantly different to the distal width (P < 0.001). This suggests that the mid ligament is the widest part, with the proximal width being the smallest. Significant correlations between various TNL parameters and other factors are shown in

Table 4.14. TNL length was correlated with foot length, 1st metatarsal length and TNL proximal width, proximal width with foot length, 1st metatarsal length, TNL length and mid-width, while its mid-width was correlated with foot length, 1st metatarsal length, proximal and distal widths, and its distal width with the 1st metatarsal length and mid width, no other correlations were observed.

Table 4.14 Significant correlations between tibionavicular ligament (TNL) dimensions and other parameters.

TNL Dimension	Correlation with	N	correlation coefficient (r)	r^2	P Value
Length	Foot Length	41	0.563	0.32	< 0.001
	1st metatarsal Length	41	0.377	0.14	0.015
	Proximal Width	41	0.663	0.44	< 0.001
Proximal Width	Foot Length	55	0.327	0.11	0.015
	1st metatarsal Length	56	0.465	0.16	0.002
	Length	41	0.663	0.44	< 0.001
	Middle Width	44	0.440	0.19	0.003
Middle Width	Foot Length	44	0.330	0.11	0.028
	1st Metatarsal Length	44	0.496	0.25	0.001
	Proximal Width	44	0.440	0.19	0.003
	Distal Width	45	0.304	0.09	0.043
Distal Width	1st Metatarsal Length	59	0.288	0.08	0.027
	Middle Width	45	0.304	0.09	0.043

4.7.4 Change in Tibionavicular Ligament (TNL) Length

In comparison to the neutral position (34.26 ± 5.76 mm), there were significant differences in length (Figure 4.29) in dorsiflexion ($P < 0.001$), plantarflexion ($P < 0.001$), inversion ($P < 0.001$) and eversion ($P < 0.001$). In addition, there were significant differences between length in dorsiflexion and plantarflexion ($P < 0.001$), and between inversion and eversion ($P < 0.001$). This indicates that TNL length is significantly stretched in plantarflexion (44.83 ± 6.74 mm) and inversion (44.76 ± 6.61 mm), while it is more relaxed in dorsiflexion (31.12 ± 4.78 mm) and eversion (32.29 ± 5.24 mm).

Length in maximum plantarflexion was positively correlated with plantarflexion PROM ($r = 0.420$, $r^2 = 0.18$, $P = 0.006$), while length in dorsiflexion was negatively correlated with the isolated eversion PROM ($r = -0.357$, $r^2 = 0.13$, $P = 0.03$). In addition, there was a positive correlation between TNL length in maximum inversion and plantarflexion PROM ($r = 0.393$, $r^2 = 0.15$, $P = 0.012$), while length in maximum eversion was negatively correlated with isolated eversion PROM ($r = 0.336$, $r^2 = 0.11$, $P = 0.042$). All other lengths had no correlation to any of the remaining PROMs.

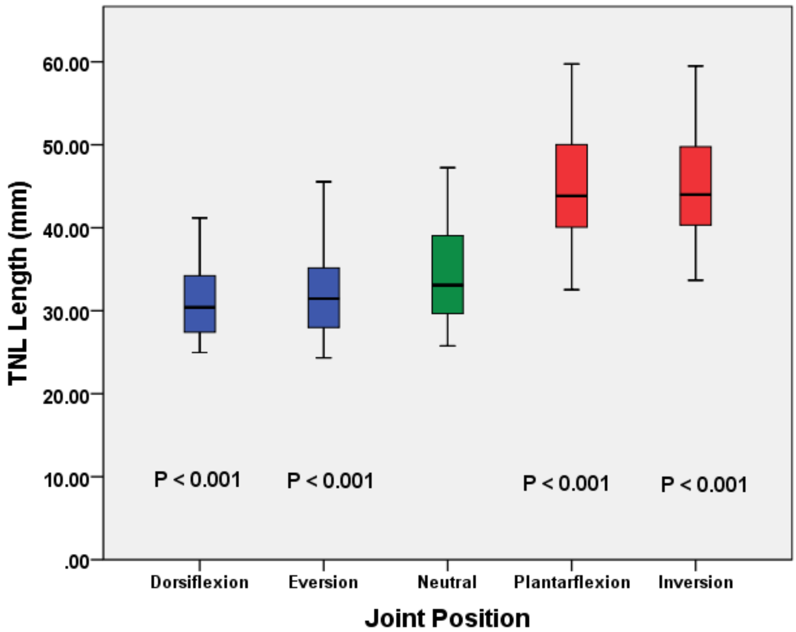

Figure 4.29 Change in the TNL length in different joint positions compared to the neutral position.

4.7.5 Tibionavicular Ligament (TNL) Bony Attachment Lengths

The TNL had different forms of attachment at its different insertion points. In 87.8% of specimens, it had a proximal bony attachment (PBA), superior no bony attachment (SNBA), talus bony attachment (TBA), inferior bony attachment (INBA) and distal bony attachment (DBA) which was a navicular bony attachment (NaBA) (Table 4.15). The second mode of attachment was seen in 7.3% of specimens, in which the TNL had only one no bony attachment while the DBA was composed of a distal talar attachment (DTBA) and a navicular attachment (NaBA). One other form was observed in 4.9% of TNLs in which there was a PBA, SNBA, TBA, INBA and a DBA composed of DTBA and NaBA. When there was only one no bony attachment length, the NBA was 22.84 ± 6.68 mm. The TBA only represented the main part of the ligament attached to the talus as there were smaller parts and deep fibres projecting to the talus at different levels. In addition, the NaBA was not measured from the first fibres attaching to the navicular, but from the main part attaching to the dorsal surface of the navicular.

Table 4.15 Tibionavicular ligament (TNL) bony attachment lengths: PBA, proximal bony attachment; SNBA, superior no bony attachment; TBA, talus bony attachment; INBA, inferior no bony attachment; DBA, distal bony attachment; NaBA, Navicular bony attachment; DTBA, distal talar bony attachment; PF, plantarflexion.

TNL Bony Attachment Lengths	**N**	**Mean**	**% total length (PF)**
PBA	28	9.7 ± 3.85	20.82%
SNBA	27	14.83 ± 3.21	3.18%
TBA	27	7.44 ± 3.41	15.97%
INBA	27	9.74 ± 4.37	20.90%
DBA	28	5.45 ± 4.45	11.70%
DTBA	4	11.29 ± 7.21	24.23%
NaBA	28	4.72 ± 2.74	10.13%

There was no difference in TNL bony attachment lengths between males and females nor between right and left sides, except for NaBA ($P = 0.032$): TNL NaBA was 5.6 ± 2.77 mm on the right and 3.36 ± 2.17 mm on the left. Foot length was correlated with both SNBA ($r = 0.457$, $r^2 = 0.21$, $P = 0.017$) and NaBA ($r = 0.426$, $r^2 = 0.18$, $P = 0.024$), age was correlated SNBA ($r = - 0.384$, $r^2 = 0.15$, $P = 0.048$) and 1st metatarsal length with SNBA ($r = 0.570$, $r^2 = 0.32$, $P = 0.002$). TNL length was correlated with the TBA ($r = 0.471$, $r^2 = 0.22$, $P = 0.017$), DBA ($r = 0.536$, $r^2 = 0.29$, $P = 0.005$) and NaBA ($r = 0.748$, $r^2 = 0.56$, $P < 0.001$), while its thickness was correlated with NaBA ($r = 0.481$, $r^2 = 0.23$, $P = 0.011$).).

4.8 Tibiospring Ligament (TSL)

The tibiospring ligament (TSL) was observed in all specimens (Figure 4.30), being the most superficial structure of the deltoid complex. It was not covered by any other band in the majority of specimens (96.8%), while partial covering by some TNL fibres was observed in 3.2% of specimens.

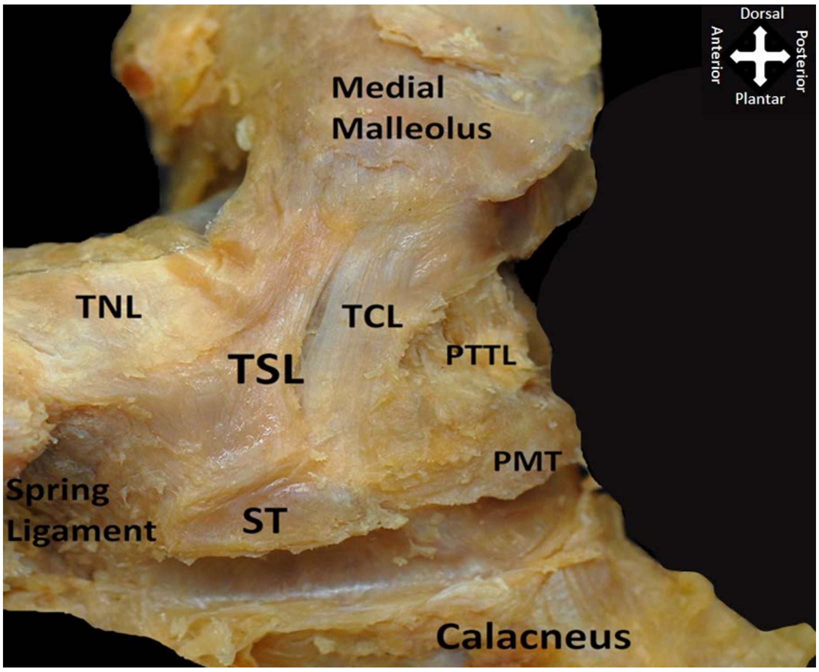

Figure 4.30 Tibiospring Ligament (TSL): ST, sustentaculum tali; PMT, posteromedial tubercle; TCL, tibiocalcaneal ligament; TSL, tibiospring ligament; TNL, tibionavicular ligament; PTTL, posterior tibiotalar ligament.

4.8.1 Proximal Attachment of the Tibiospring Ligament (TSL)

The proximal attachment (Figure 4.31) was to the medial malleolus, being to the anterior border and medial surface of the anterior colliculus (60.4%), medial surface of the anterior colliculus (20.8%), anterior border of the anterior colliculus (17%), and to the anterior and medial surface of the anterior colliculus as well as medial surface of the medial malleolus superior to the border of the intercollicular groove (1.9%). There was no difference in TSL origin between males and females or between right and left sides.

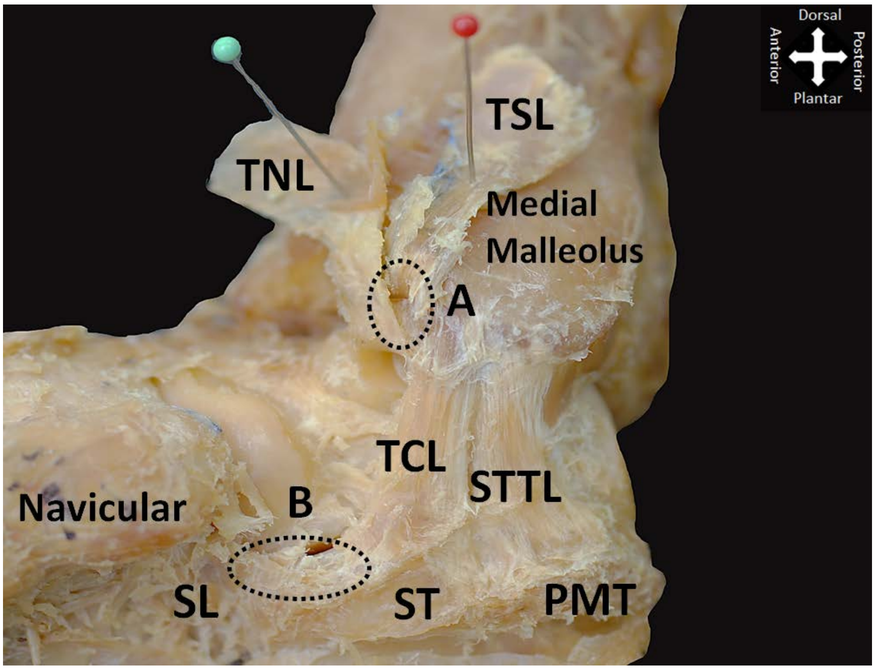

Figure 4.31 Proximal (dotted circle A) and distal (dotted circle B) attachment of the tibiospring (TSL); SL, spring ligament; ST, sustentaculum tali; PMT, posteromedial tubercle; TCL, tibiocalcaneal ligament; TNL, tibionavicular ligament; STTL, superficial tibiotalar ligament.

4.8.2 Distal Attachment of the Tibiospring Ligament (TSL)

The distal attachment of the TSL (Figure 4.31) spread widely into the fibrocartilage, passing fibres to the spring ligament and sustentaculum tali (78.3%), or only to the connecting fibres to the spring ligament (15%), or only to the sustentaculum tali (6.7%). The distal TSL attachment did not differ between genders or foot side. When the TSL had an attachment to the sustentaculum tali, it attached to its superior, anterosuperior and superoposterior aspects in 72.1%, 23.3% and 4.7% respectively. Gender and foot side had no effect on the sustentaculum tali attachment.

4.8.3 Tibiospring Ligament (TSL) Orientation

The TSL passed laterally from the medial malleolus to its distal attachment (Figures 4.32 – 4.33); however, its orientation varied in different joint positions (Table 4.16). The ligament had anteroinferior and posteroinferior orientations in all joint positions: an inferior orientation was observed in neutral, dorsiflexion and eversion. In plantarflexion and inversion, the ligament had an anteroinferior orientation crossing distally and then curving to become posteroinferior.

Table 4.16Tibiospring ligament orientation in different joint position.

Joint Position	Anteroinferior	Posteroinferior	Inferior	Anteroinferior / Posteroinferior
Neutral	82.1%	10.7%	7.1%	0%
Dorsiflexion	85.7%	3.6%	10.7%	0%
Plantarflexion	20.7%	75.9%	0%	3.4%
Inversion	21.4%	75%	0%	3.6%
Eversion	82.1%	3.6%	14.3%	0%

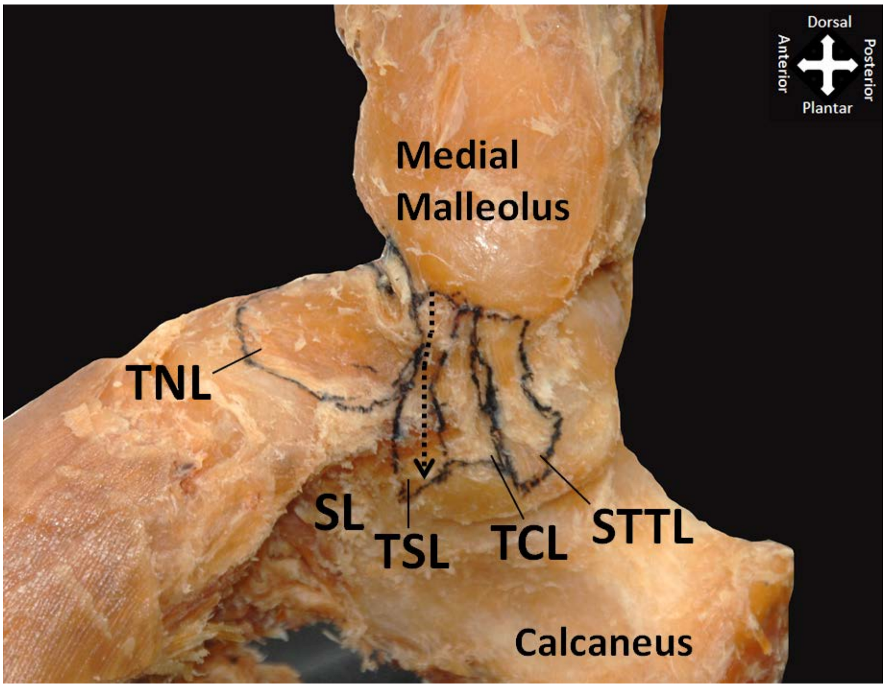

Figure 4.32 Tibiospring ligament (TSL) orientation (black dotted arrow) in neutral position: SL, spring ligament; TNL, tibionavicular ligament; TCL, tibioalcaneal ligament; STTL, superficial tibiotalar ligament.

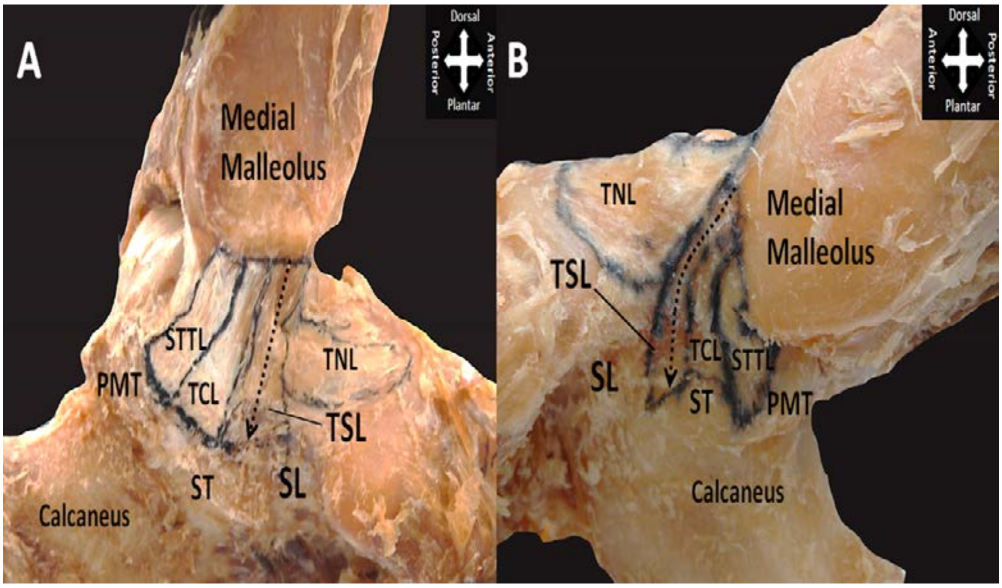

Figure 4.33 Tibiospring (TSL) orientation (black dotted arrows) in dorsiflexion (A) and plantarflexion (B): SL, spring ligament; ST, sustentaculum tali; PMT, posteromedial tubercle; TNL, tibionavicular ligament; TCL, tibiocalcaneal ligament; STTL, superficial tibiotalar ligament.

4.8.4 Tibiospring Ligament (TSL) Dimensions

The mean length, mid-width and thickness of the TSL were 31.48 ± 6.41 mm, 5.64 ± 1.57 mm and 0.79 ± 0.3 mm respectively (Table 4.17). The distal width of TSL was 8.08 ± 2.57 mm: when it had a distal attachment to the sustentaculum tali 5.32 ± 2.2 mm of this width attached to it. TSL length was significantly different between genders, being 35.36 ± 6.51 mm in males and 28.97 ± 5.02 mm in females. However, there was no difference in widths or thickness between males and females. There was also no difference in TSL dimensions between right and left sides.

Table 4.17 Tibiospring (TSL) dimensions: ST, sustentaculum tali.

TSL Dimension		**N**	**Mean ± SD (mm)**
Length	**Neutral**	51	31.48 ± 6.41
Width	**Proximal**	62	5.08 ± 2.22
	Middle	53	5.64 ± 1.57
	Distal	62	8.08 ± 2.57
	Width to ST	32	5.32 ± 2.2
Thickness	**Middle**	48	0.79 ± 0.3

The proximal width was not different to the mid-width; however, the distal width was significantly different to the proximal ($P < 0.001$) and mid-widths ($P < 0.001$). This suggests that distal width is always significantly widest; while the proximal and middle widths are smaller. Analysis of the TSL dimensions showed a number of correlations with different parameters (Table 4.18). TSL length was correlated with foot length, 1st metatarsal length, proximal width, mid-width, distal width and NBA; but not with age, thickness, PBA or distal attachment (DA). In addition, the proximal width was correlated with foot length, 1st metatarsal length, TSL length, mid-and distal widths; however, there was no correlation between proximal width and age, PBA or thickness.

The mid-width was correlated with TSL length, proximal and distal width and distal width with age, foot length, TSL length, proximal width, mid-width and thickness, while TSL thickness was correlated with age and distal width.

Table 4.18 Significant correlations between tibiospring (TSL) dimensions and different parameters: NBA, no bony attachment.

TSL Dimension	Correlation with	N	correlation coefficient (r)	r^2	P Value
Length	Foot Length	50	0.482	0.23	< 0.001
	1st Metatarsal Length	50	0.462	0.21	0.001
	Proximal Width	51	0.327	0.11	0.019
	Middle Width	50	0.379	0.14	0.007
	Distal Width	51	0.342	0.12	0.014
	NBA	28	0.560	0.31	0.002
Proximal Width	Foot Length	59	0.328	0.11	0.011
	1st Metatarsal Length	60	0.291	0.08	0.024
	Length	51	0.327	0.11	0.019
	Middle Width	53	0.452	0.2	0.001
	Distal Width	61	0.549	0.3	< 0.001
Mid-width	Length	50	0.379	0.14	0.007
	Proximal Width	53	0.452	0.2	0.001
	Distal Width	52	0.570	0.32	< 0.001
Distal Width	Age	62	- 0.283	0.08	0.026
	Foot Length	60	0.264	0.07	0.041
	Length	51	0.342	0.12	0.014
	Proximal Width	61	0.549	0.3	< 0.001
	Middle Width	52	0.570	0.32	< 0.001
	Thickness	48	0.309	0.1	0.032
Thickness	Age	48	- 0.305	0.09	0.035
	Distal Width	48	0.309	0.1	0.032

4.8.5 Change in Tibiospring Ligament (TSL) Length

The TSL changed length (Figure 4.34) in different joint positions; however, these changes were not different in dorsiflexion (31.47 ± 5.82 mm), plantarflexion (31.3 ± 6.06 mm), inversion (30.63 ± 6.65 mm) and eversion (31.8 ± 5.92 mm) compared to neutral (31.56 ± 6.53 mm). There was no significant difference in TSL length between dorsiflexion and plantarflexion; however, the length in inversion was significantly different from that in eversion (P = 0.009). This suggests that the TSL becomes increasingly taut in eversion compared to inversion, in which the ligament becomes shorter. TSL length in maximum inversion was correlated with isolated inversion PROM (r = - 0.317, r^2 = 0.1, P = 0.041). Other changes in TSL length were not correlated with PROM in other joint positions.

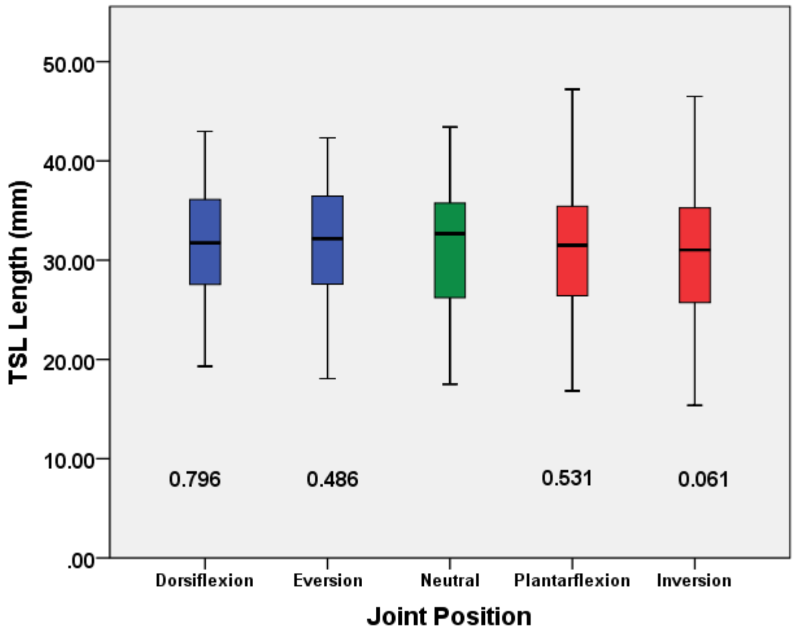

Figure 4.34 Changes in the tibiospring (TSL) length in different joint positions compared to neutral.

4.8.6 Tibiospring Ligament (TSL) Bony Attachment Lengths

The TSL proximal bony attachment length comprised 17% of the total ligament length, while the distal attachment was 23.66% (Table 4.19). The TSL distal attachment (DA) was not to bone as it crossed distally to blend with the fibrocartilage layer connecting and blending with the spring ligament, although it may also attach to the sustentaculum tali. The free length of the ligament, i.e. the length that had no bony attachment comprised 59.37% of TSL total length.

Correlation between TSL NBA and foot length ($r = 0.600$, $r^2 = 0.36$, $P = 0.001$), TSL length ($r = 0.560$, $r^2 = 0.31$, $P = 0.012$) and TSL DA ($r = -0.452$, $r^2 = 0.2$, $P = 0.012$) were observed, while TSL DA was correlated with TSL NBA ($r = -0.452$, $r^2 = 0.2$, $P = 0.012$).

Table 4.19 Tibiospring (TSL) bony attachment lengths: PBA, proximal bony attachment; NBA, no bony attachment; DBA, distal bony attachment.

TSL Bony Attachment Length	N	Mean ± SD (mm)	% of the total length (PF)
PBA	30	5.84 ± 3.01	17.00%
NBA	30	20.4 ± 4.55	59.37%
DA	30	8.13 ± 3.47	23.66%

4.8.7 Relations to Other Bands

The TSL was continuous with the TNL in 84.3% of specimens and partially continuous with the TNL in the remaining 15.7%. It blended with the superficial layer of the TNL, but did not extend to attach to the deeper fibres. It was also continuous with the TCL in 6.5% of specimens, being separated from each other at different levels as well as being completely separated in 84.8% and 8.7% respectively (Figure 4.35). Occasionally some fibre fasciculation was observed; however, this was not considered as fasciculation into independent bands. In one specimen a band deep to the TSL was observed which could be part of the TSL, as it had an origin from the medial surface of the anterior colliculus and inserted distally to the medial surface of the talus as well as to the posterosuperior part of the sustentaculum tali.

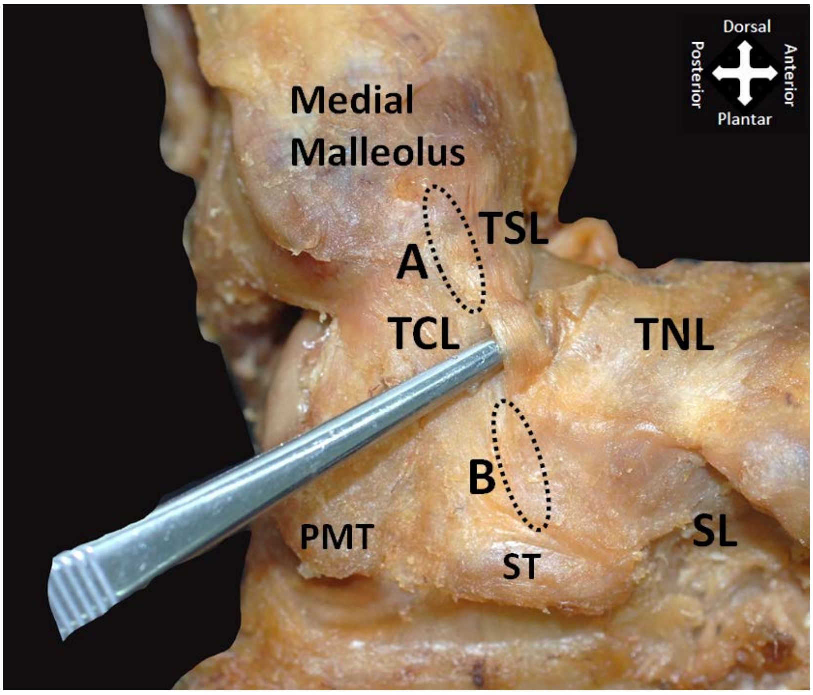

Figure 4.35 The tibiospring ligament (TSL) attaching to the tibiocalcaneal ligament (TCL) proximally (dotted circle A) and distally (dotted circle B), but there is no continuity between them: TNL, tibionavicular ligament; PMT, posterior tibiotalar tubercle; ST, sustentaculum tali; SL, spring ligament.

4.9 Tibiocalcaneal Ligament (TCL)

The tibiocalcaneal ligament (TCL) (Figure 4.36) was a consistent band of the superficial layer of the medial collateral (deltoid) ligament. It was partially covered by the TSL anteriorly in 88.3% of specimens, in 6 of feet it was not covered by any other band: in one specimen the TSL completely covered the TCL.

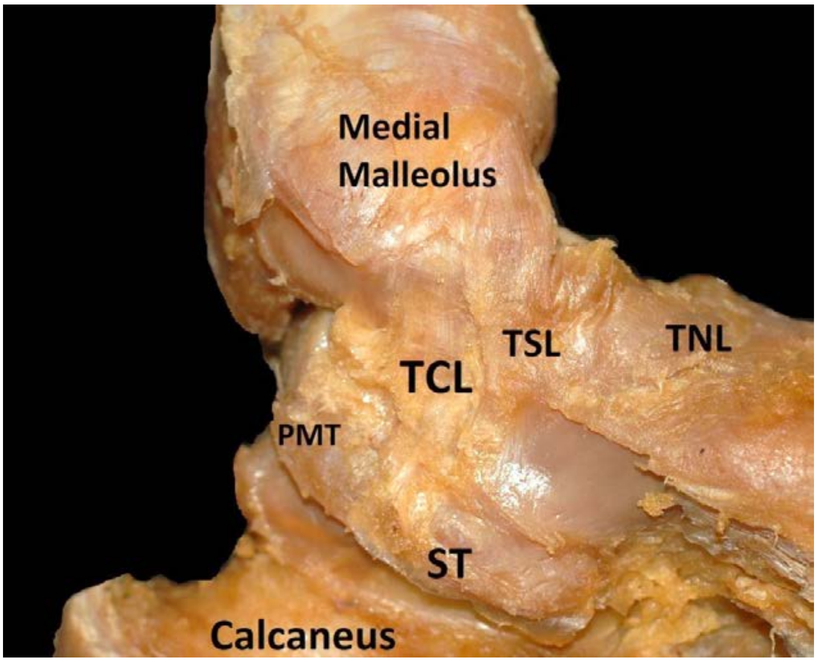

Figure 4.36 Tibiocalcaneal ligament (TCL); TSL: tibiospring ligament, TNL: tibionavicular ligament, PMT: posteromedial tubercle of the talus, ST: sustentaculum tali.

4.9.1 Proximal Attachment of the Tibiocalcaneal Ligament (TCL)

There was variation in the proximal attachment of the TCL: it originated from the medial surface of the anterior colliculus of the medial malleolus and medial surface of the medial malleolus superior to the border of the intercollicular groove in 56.9% of specimens (Figure 4.37), while it was attached proximally to only the medial surface of the anterior colliculus in 32.8%. In 5.2% of specimens, the TCL originated from the medial surface of the anterior and posterior colliculi as well as superior to the border of the intercollicular groove. Two specimens (3.4%) had their proximal attachment only to the medial surface superior to the border of the intercollicular groove, while in one specimen (1.7%) the TCL attached proximally to the medial surface and posterior edge of the anterior colliculus as well as to the medial surface of the medial malleolus just superior to the border of the intercollicular groove. There was no variation in the

TCL origin between males and females or between right and left sides. When the TCL had a proximal attachment to the medial surface of the medial malleolus superior to the intercollicular groove the average distance between its mid proximal attachment and the edge of the intercollicular groove was 3.59 ± 1.4 mm. This distance did not differ between genders or foot side. In addition, the TCL mid proximal attachment distance to the intercollicular groove edge was not correlated with age, foot length, 1st metatarsal length or TCL length.

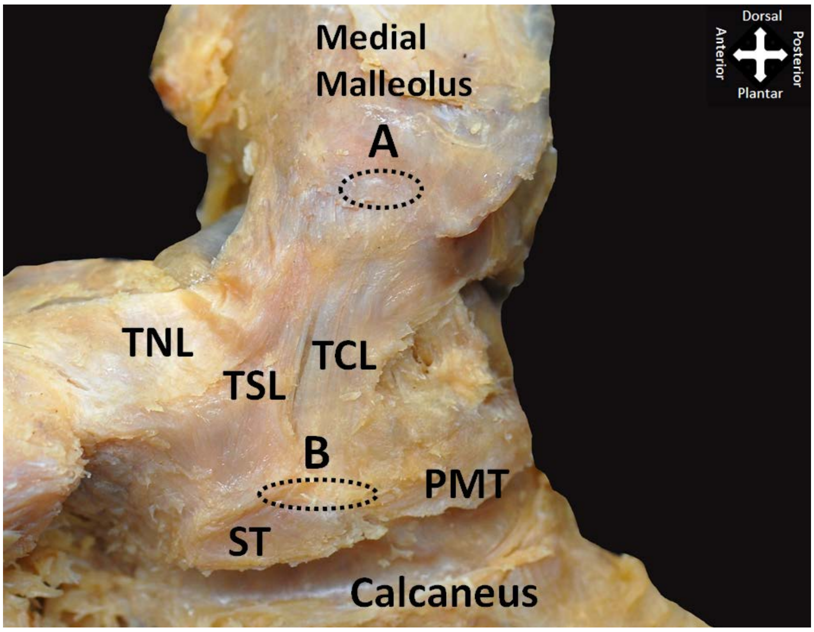

Figure 4.37 Proximal (dotted circle A) and distal (dotted circle B) attachments of the tibiocalcaneal ligament (TCL); TNL, tibionavicular ligament; TSL, tibiospring ligament; ST, sustentaculum tali; PMT: talar posteromedial tubercle.

4.9.2 Distal Attachment of the Tibiocalcaneal Ligament (TCL)

The TCL had a variable distal attachment (Figure 4.38), including the calcaneus, talus, sustentaculum tali, spring ligament and talar posteromedial tubercle. As shown in Figure 4.38, the major distal attachments were to the spring ligament (connecting fibres) and sustentaculum tali (36.21%), sustentaculum tali and talar posteromedial tubercle (27.59%) and the sustentaculum tali (18.97%). These variations showed no difference between males and females or between right and left sides.

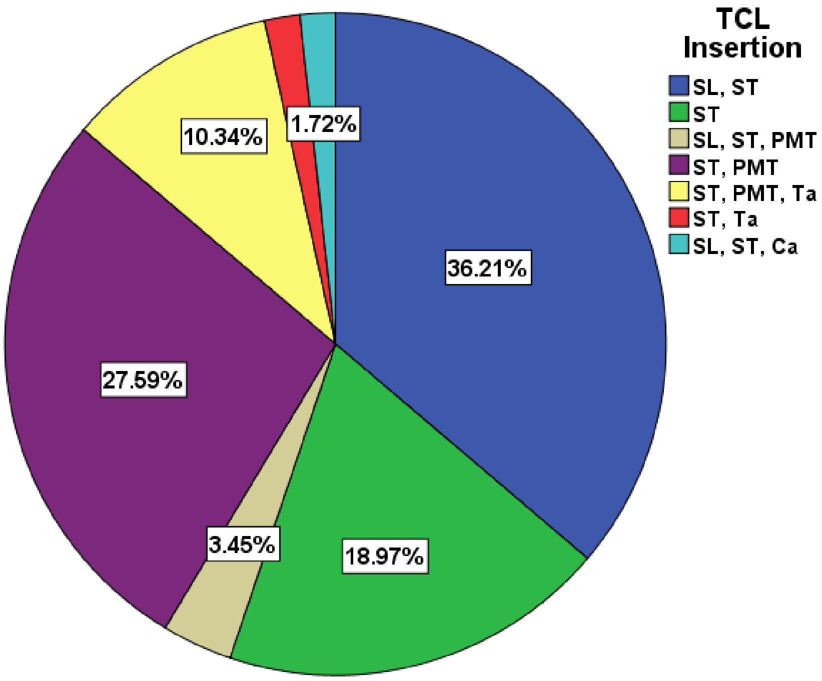

Figure 4.38 Distal attachments of the Tibiocalcaneal ligament (TCL): SL, spring ligament; ST, sustentaculum tali; PMT, talar posteromedial tubercle; Ta, talus (medial surface); Ca, calcaneus (medial surface).

A distal attachment of the TCL to the sustentaculum tali was observed in all specimens; however, the exact site of attachment varied (Table 4.20), including to its superior, posterior, anterior and medial aspects. The main TCL sustentaculum tali insertions were observed to be into the superior and posterior (51.9%), posterior (18.5%) and superior (14.8%) aspects. The TCL also inserted distally onto the talar posteromedial tubercle in 41.38% of specimens, being mainly to its anterior and superior (31.8%) and anterior

(63.6%) aspects (Table 4.20). Variations in the TCL insertion sites into the sustentaculum tali and talar posteromedial tubercle did not differ between genders or foot side.

Table 4.20 Distal attachment of the TCL to sustentaculum tali and talar posteromedial tubercle.

Sustentaculum tali attachment	**N**	**Occurrence**	**Posteromedial tubercle attachment**	**N**	**Occurrence**
Superior, posterior	14	51.90%	Anterior, superior	7	31.80%
Superior, posterior, medial	2	7.40%	Anterior	14	63.6%
Posterior	5	18.50%	Superior	1	4.5%
Superior	4	14.80%			
Posterior, medial	1	3.70%			
Anterior, superior, posterior	1	3.70%			

4.9.3 Tibiocalcaneal Ligament (TCL) Orientation

The tibiocalcaneal ligament crossed laterally (Figures 4.39 and 4.40) being oriented differently according to joint position. In neutral the TCL passed anteroinferiorly (25%), posteroinferiorly (60.7%) or inferiorly (14.3%), while it passed anteroinferiorly (27.6%), posteroinferiorly (37.9%) or inferiorly (34.5%) in dorsiflexion. In plantarflexion, the TCL passed anteroinferiorly (6.7%) or posteroinferiorly (93.3%), while in inversion it passed anteroinferiorly (6.9%) or posteroinferiorly (93.1%). Moreover, in eversion the TCL passed in an anteroinferior, posteroinferior and inferior directions in 21.4%, 39.3% and 39.3% of specimens respectively.

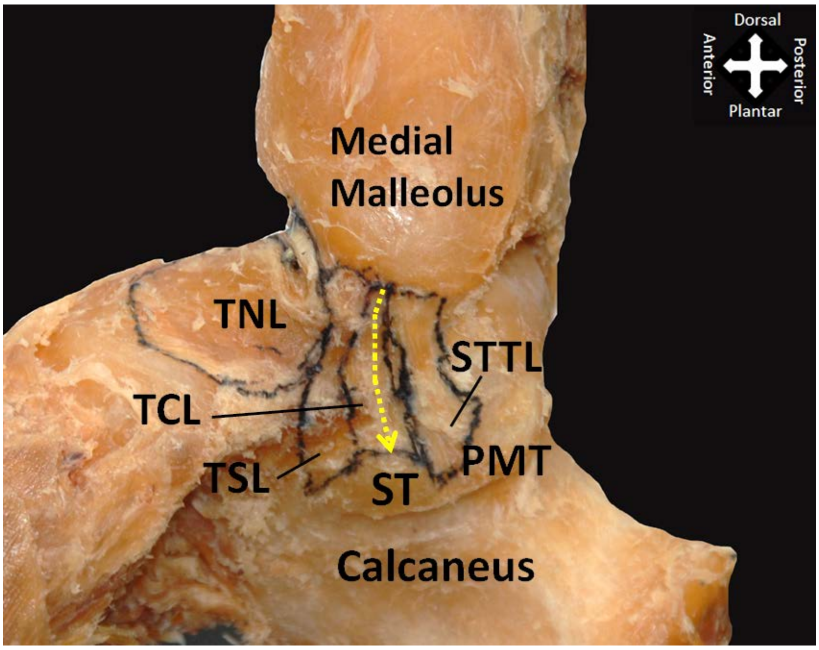

Figure 4.39 Tibiocalcaneal ligament (TCL) orientation (yellow dotted arrow) in neutral position: TNL, tibionavicular ligament; TSL, tibiospring ligament; STTL, superficial tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

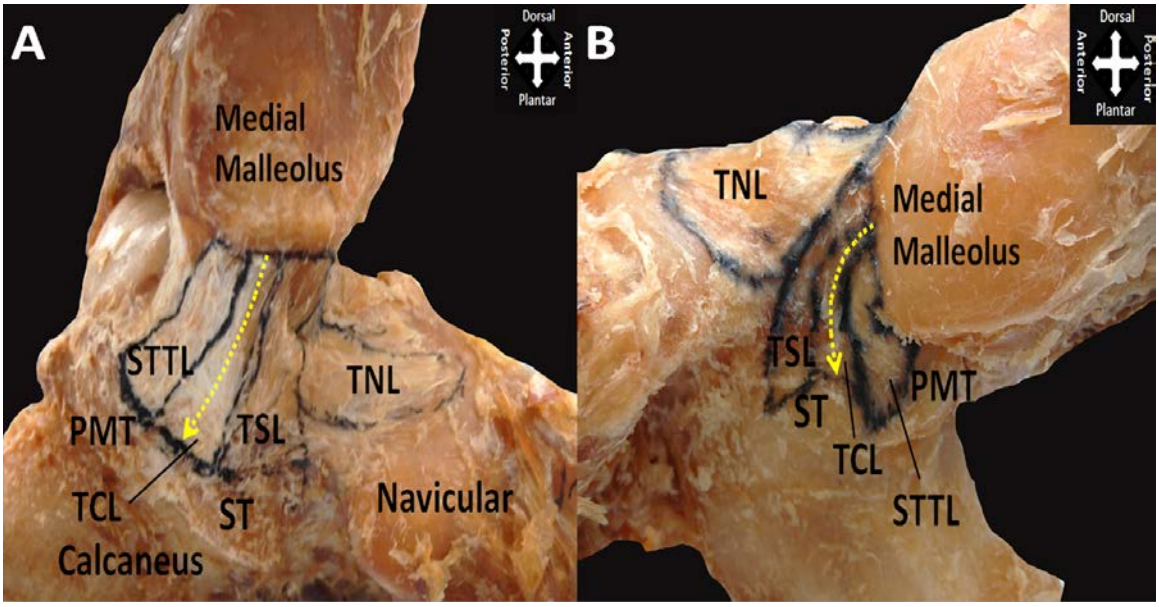

Figure 4.40 Tibiocalcaneal (TCL) orientation (yellow dotted arrows) in dorsiflexion (A) and plantarflexion (B): TNL, tibionavicular ligament; TSL, tibiospring ligament; STTL, superficial tibiotalar ligament; ST, sustentaculum tali; PMT, talar posteromedial tubercle.

4.9.4 Tibiocalcaneal Ligament (TCL) Dimensions

The tibiocalcaneal ligament had a mean length, mid width and thickness of 29.48 ± 4.36 mm, 5.21 ± 1.64 mm and 0.96 ± 0.91 mm respectively (Table 4.21). TCL length was significantly different between males and females ($P < 0.001$), being 32.45 ± 4.11 mm in males and 27.54 ± 3.34 mm in females. However, mid width and thickness were not different between genders. There was a significant difference in proximal width between right and left sides, being 5.56 ± 1.57 mm on the right and 4.55 ± 1.91 mm on the left. However, the TCL length, mid width, distal width and thickness did not differ between right and left sides. There was no difference in TCL proximal width and mid width; however distal width was significantly different to both the proximal ($P < 0.001$) and mid widths, showing that the TCL is significantly wider distally compared to proximally and at its middle.

Table 4.21 Tibiocalcaneal ligament (TCL) length, width and thickness.

TCL Dimension		N	Mean ± SD (mm)
Length	**Neutral**	48	29.48 ± 4.36
Width	**Proximal**	55	5.06 ± 1.8
	Mid	51	5.21 ± 1.64
	Distal	55	8.3 ± 3.03
	to sustentaculum tali	26	5.92 ± 3.14
Thickness	**Mid**	49	0.96 ± 0.91

TCL length was correlated with foot length ($r = 0.356$, $r^2 = 0.13$, $P = 0.014$), 1st metatarsal length ($r = 0.334$, $r^2 = 0.11$, $P = 0.022$) and mid width ($r = 0.358$, $r^2 = 0.13$, $P = 0.013$), while its proximal width was correlated with the mid width ($r =$

0.622, r^2 = 0.39, P < 0.001). TCL mid width was correlated with length (r = 0.358, r^2 = 0.13, P = 0.013), proximal (r = 0.622, r^2 = 0.39, P < 0.001) and distal (r = 0.392, r^2 = 0.15, P = 0.005) width, and distal width was correlated with the mid width (r = 0.392, r^2 = 0.15, P = 0.005) only.

4.9.5 Changes in Tibiocalcaneal Ligament (TCL) Length

In different joint positions there was a change in TCL length (Figure 4.41); compared with neutral (29.48 ± 4.36 mm) the length in dorsiflexion (29.65 ± 4.43 mm) and eversion (29.56 ± 4.15 mm) were not different; however a significant difference was found in plantarflexion (26.83 ± 4.32 mm) (P < 0.001) and inversion (25.86 ± 4.63 mm) (P < 0.001) (Figure 4.41). In addition, there were significant differences in the mean length between dorsiflexion and plantarflexion (P < 0.001) and between inversion and eversion (P < 0.001), with the length in plantarflexion being significantly shorter than dorsiflexion, while in eversion the ligament was more taut than in inversion.

TCL length in dorsiflexion was correlated with maximum isolated inversion PROM (r = - 0.328, r^2 = 0.11 P = 0.11), while maximum isolated eversion PROM was correlated with TCL length in neutral (r = - 0.423, r^2 = 0.18, P = 0.006), dorsiflexion (r = - 0.443, r^2 = 0.2, P = 0.004), plantarflexion (r = - 0.334, r^2 = 0.11, P = 0.033), inversion (r = - 0.365, r^2 = 0.13, P = 0.019) and eversion (r = - 0.444, r^2 = 0.2, P = 0.004). .

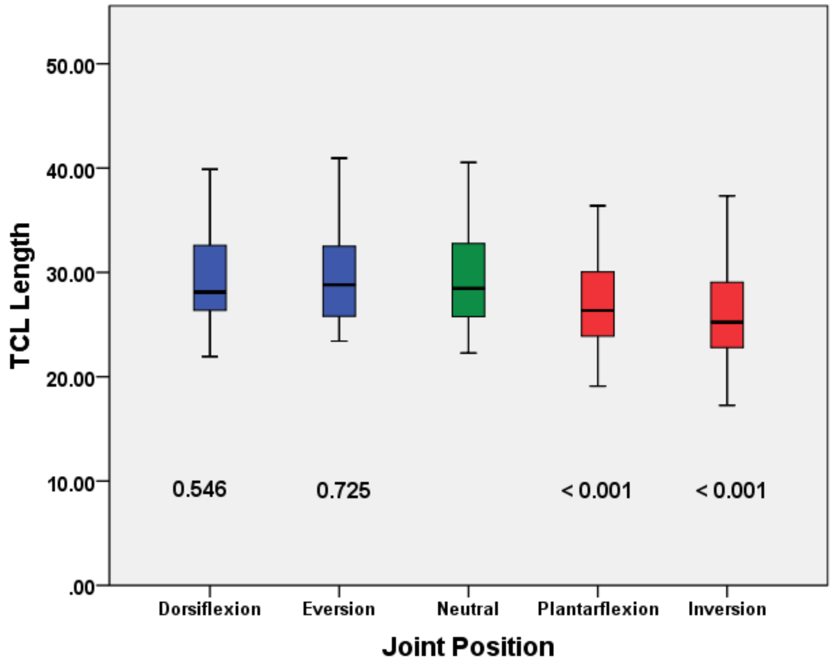

Figure 4.41 Change in the length of the tibiocalcaneal ligament (TCL) in different joint positions compared to the neutral position.

4.9.6 Tibiocalcaneal (TCL) Bony Attachment Lengths

The TCL had 18.15% of its length attached to the medial malleolus proximally, while 19.76% formed the distal bony attachment length (Table 4.22) with the remaining 62.09% of the total length being free. TCL bony attachment length was not different between males and females or between right and left sides. TCL NBA was correlated with 1st metatarsal length (r = 0.393, r^2 = 0.15, P = 0.032), TCL length (r = 0.542, r^2 = 0.29, P = 0.002) and TCL DBA (r = - 0.383, r^2 = 0.15, P = 0.034), while TCL DBA was correlated with TCL NBA (r = - 0.383, r^2 = 0.15, P = 0.034).

Table 4.22 Tibiocalcaneal ligament (TCL) proximal (PBA) and distal (DBA) bony attachment lengths together with the non-bony attachment length.

	N	Mean (mm)	% of the total length (PF)
TCL PBA	31	4.97 ± 3.33	18.15%
TCL NBA	31	17 ± 4.75	62.09%
TCL DBA	31	5.41 ± 3	19.76%

4.9.7 Relation to Other Ligament Bands

The TCL was continuous with the superficial tibiotalar ligament (STTL) in 58.5% of specimens, being separated at different levels of its length in the remainder. These showed no difference between genders or foot side. The TCL separated from the STTL proximally 9.95 ± 3.11 mm distal to the TCL proximal attachment. In 50% of specimens the TCL was free for 3.95 ± 2.19 mm proximally. The TCL separated from the STTL distally 7.97 ± 3.85 mm proximal to the TCL distal attachment: in 27.82% of these the TCL was free for 4.41 ± 1.3 mm distally from the STTL.

Fibrous tissue connecting the STTL and TCL (Figure 4.42) was observed to project to the posteromedial surface of the calcaneus filling the gap between the sustentaculum tali and talar posteromedial tubercle: it is suggested that this could act as a tensing structure stabilising the calcaneus and talus medially. In addition, some TCL projecting fibres projected deep to have a small connection with the tibionavicular ligament (TNL). Moreover, in one specimen some TCL fibres projected to blend with the PTTL. In other cases, the TCL was clearly separated from the deep layer of the deltoid, especially in its middle part (i.e. the NBA part of the TCL). However, some fibres of the proximal and distal parts may interact with a small part of the deep layer of the deltoid ligament. TCL fibre fasciculation was observed but did not constitute independent bands.

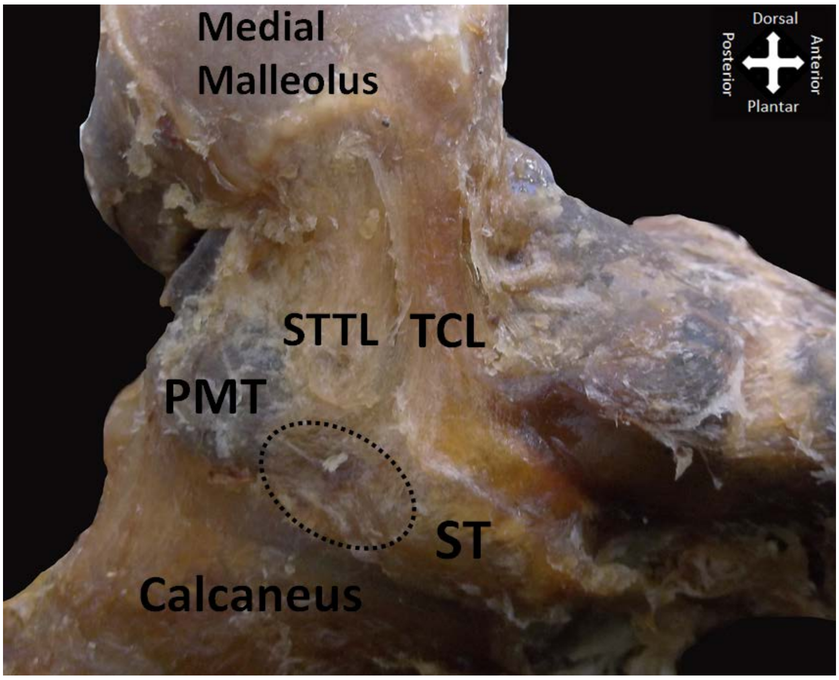

Figure 4.42 Fibres projecting distally from the tibiocalcaneal ligament (TCL) and superficial tibiotalar ligament (STTL) (black dotted circle) joining the fibrous tissues that connect the posteromedial tubercle (PMT) and sustentaculum tali (ST).

4.10 Superficial Posterior Tibiotalar Ligament (STTL)

The superficial tibiotalar ligament (STTL) (Figure 4.43) was observed in 92.2% of specimens, being absent in the remaining 7.8%: there was no association between the STTL and gender or foot side. The majority of STTLs (86%) were not covered by any band of the deltoid ligament; however, the TCL partially covered part of the STTL in 14% of specimens. The presence of an STTL and its relation to the TCL did not differ between males and females or between right and left sides.

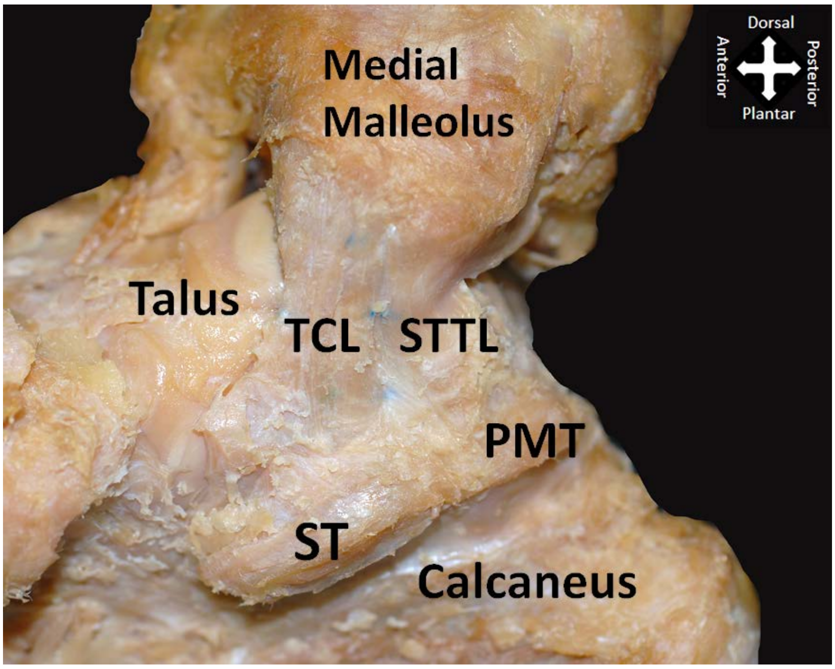

Figure 4.43 Superficial tibiotalar ligament (STTL); tibionavicular and tibiospring parts of the deltoid have been removed; TCL, tibiocalcaneal ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

4.10.1 Proximal Attachment of the Superficial Tibiotalar Ligament (STTL)

The proximal attachment of the STTL (Figure 4.44) was to the medial malleolus of the tibia, the majority of specimens (70%) being to the medial malleolus superior to the edge of the intercollicular groove (IG) and anterior to the posterior colliculus. The medial surface of the anterior colliculus was a proximal attachment site of the STTL in some specimens: other variable proximal attachment sites for the STTL are shown in Table 4.23. The STTL proximal attachment was 2.23 ± 1.43 mm proximal to the edge of the medial malleolar intercollicular groove. The variation of the STTL proximal attachment as well as the distance between the proximal attachment and the intercollicular groove did not differ between genders or foot side. The distance between the proximal attachment and the edge of the intercollicular groove was correlated with foot length (r = 0.409, r^2 = 0.17, P = 0.012) and 1st metatarsal length (r = 0.339, r^2 = 0.11, P = 0.04).

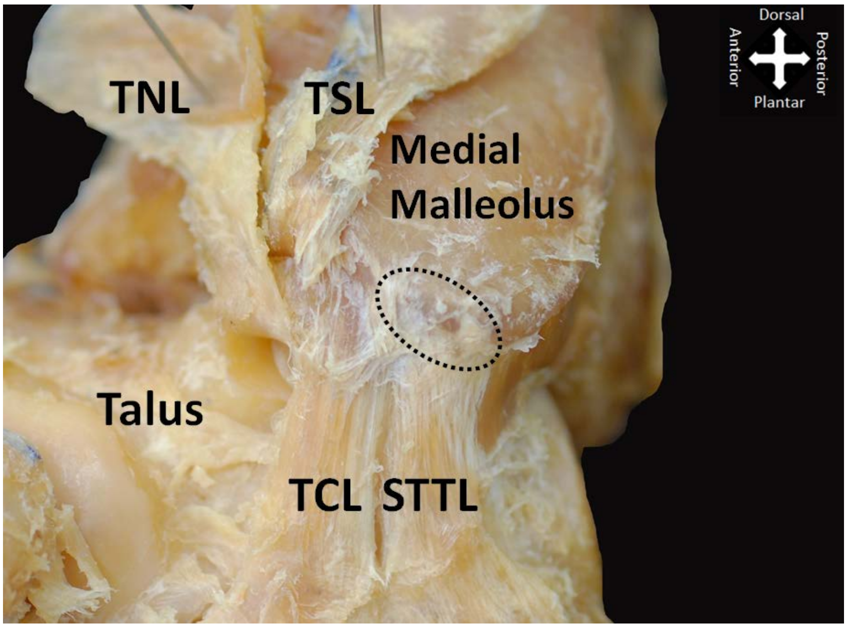

Figure 4.44 Proximal attachment (dotted circle) of the superficial tibiotalar ligament (STTL): TCL, tibiocalcaneal ligament; tibionavicular ligament (TNL) and tibiospring ligament (TSL) have been reflected.

Table 4.23 Proximal attachment of the superficial tibiotalar ligament (STTL); IG (intercollicular groove).

STTL Proximal Attachment	**N**	**Occurrence**
Superior to the IG, anterior to posterior colliculus	35	70%
anterior to posterior colliculus	2	4%
Superior to the IG, anterior colliculus (medial surface)	3	6%
Anterior colliculus (medial surface), anterior to posterior colliculus	3	6%
Superior to IG, anterior colliculus (medial surface), anterior to posterior colliculus	2	4%
Anterior colliculus (medial surface)	1	2%
Posterior colliculus (anterior part)	1	2%
Superior to the IG	3	6%

4.10.2 Distal Attachment of the Superficial Tibiotalar Ligament (STTL)

The STTL had variable sites of distal attachment including the medial surface of the talus (95.8%), the talar posteromedial tubercle (89.3%) (Figure 4.45) and the sustentaculum tali (17%). Table 4.24 shows the different STTL distal attachments with about half of the specimens having the STTL inserting distally to the anterior and superior aspects of the posteromedial tubercle as well as to the medial surface of the talus. Other descriptions of the STTL distal attachments are shown in Table 4.24. Variations in STLL insertions were not associated with gender or foot side.

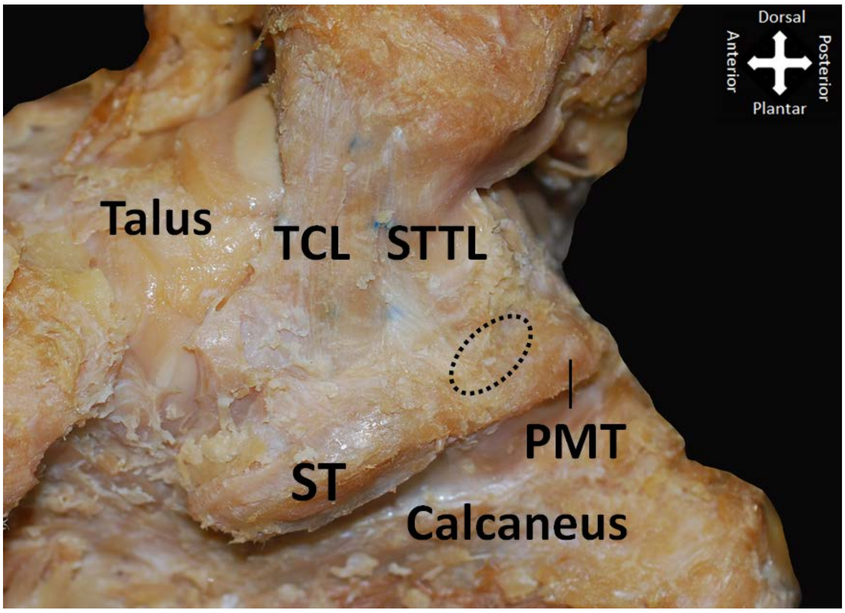

Figure 4.45 Distal attachment (dotted circle) of the superficial tibiotalar ligament (STTL): TCL, tibiocalcaneal ligament; ST, sustentaculum tali; PMT, posteromedial tubercle; tibionavicular and tibiospring parts of the deltoid have been removed.

Table 4.24 Distal attachment of the superficial tibiotalar ligament (STTL); PMT (talar posteromedial tubercle), ST (sustentaculum tali).

STTL Distal Attachment	**Occurrence**
PMT (anterior, superior), talus (medial surface)	46.80%
PMT (anterior, superior), ST (posterosuperior), talus (medial surface)	8.50%
PMT (anterior, superior), ST (posterosuperior)	2.10%
PMT (superior), talus (medial surface)	21.30%
PMT (anterior, superior), ST (posterior), talus (medial surface)	4.30%
Talus (medial surface anterosuperior to the PMT)	8.50%
ST (posterosuperior), talus (medial surface anterosuperior to the PMT)	2.10%
PMT (superior)	2.10%
PMT (superior, medial), talus (medial surface)	2.10%
PMT (anterior, superior, posterior), talus (medial surface)	2.10%

4.10.3 Superficial Tibiotalar Ligament (STTL) Orientation

The STTL passed laterally between its proximal and distal attachments. A posteroinferior orientation (Figures 4.46 and 4.47) was observed in neutral (96.4%), dorsiflexion (89.3%), plantarflexion (100%), inversion (100%) and eversion (92.6%), while an inferior orientation was observed in 3.6%, 10.7% and 7.4% in neutral, dorsiflexion and eversion respectively.

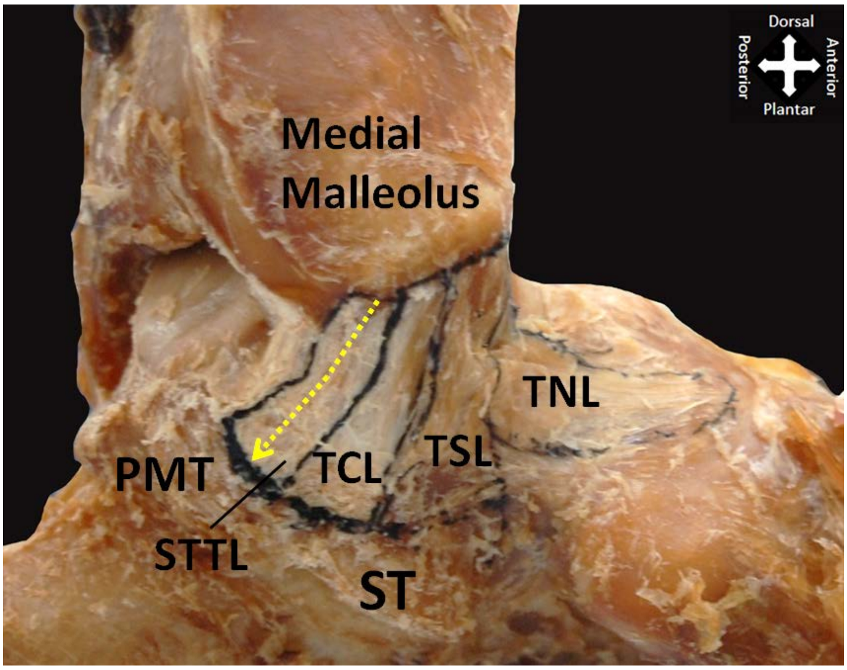

Figure 4.46 Superficial tibiotalar ligament (STTL) orientation (yellow dotted arrow) in the neutral position: TCL, tibiocalcaneal ligament; TSL, tibiospring ligament; TNL, tibionavicular ligament; ST, sustentaculum tali; PMT, talar posteromedial tubercle.

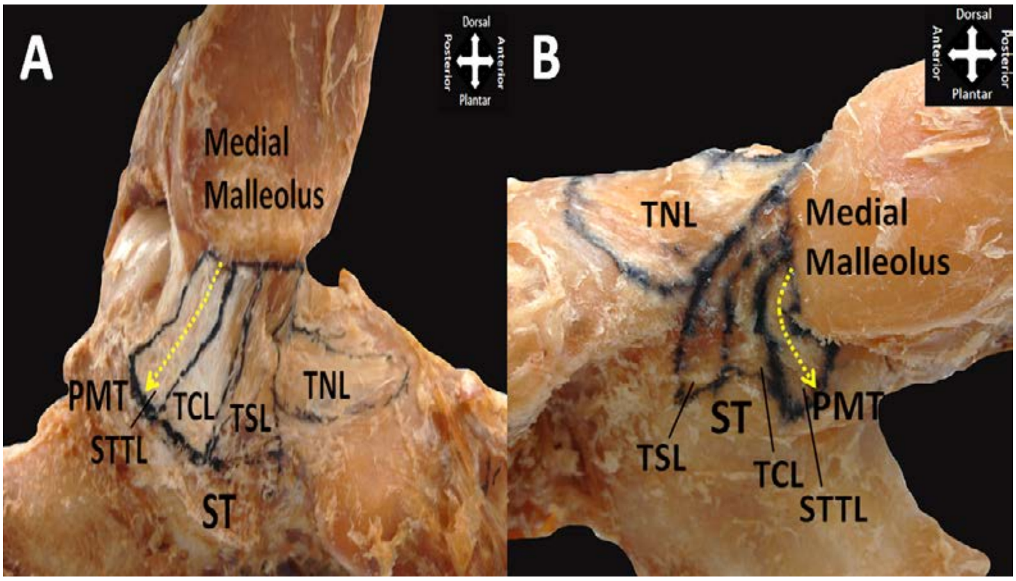

Figure 4.47 Superficial tibiotalar ligament (STTL) orientation (yellow dotted arrows) in dorsiflexion (A) and plantarflexion (B): TNL, tibionavicular ligament; TSL, tibiospring ligament; TCL, tibiocalcaneal ligament; ST, sustentaculum tali; PMT, talar posteromedial tubercle..

4.10.4 Superficial Tibiotalar Ligament (STTL) Dimensions

The STTL had a mean length of 23.08 ± 3.75 mm and proximal, mid and distal widths of 5.23 ± 4.41 mm, 5.06 ± 1.45 mm and 5.66 ± 2.06 mm respectively: its thickness was 0.89 ± 0.92 mm (Table 4.25). The STTL proximal, mid and distal widths and thickness did not differ between males and females; however, STTL length was significantly different between genders ($P < 0.001$), being 25.63 ± 3.85 mm in males and 21.46 ± 2.66 mm in females. None of the STTL dimensions differed between right and left sides. There was no difference between the mid and proximal widths; however, a significant difference in the proximal ($P = 0.006$) and mid ($P = 0.003$) width compared to the distal width was observed. This suggests that the distal width is significantly wider than the proximal and mid widths. STTL length was correlated with foot length ($r = 0.437$,

r^2 = 0.19, P = 0.002) and 1st metatarsal length (r = 0.468, r^2 = 0.22, P = 0.001), while STTL proximal width was correlated with both age (r = - 0.322, r^2 = 0.1, P = 0.015) and mid width (r = 0.393, r^2 = 0.15, P = 0.008). Mid width was correlated with proximal (r = 0.393, r^2 = 0.15, P = 0.008) and distal (r = 0.609, r^2 = 0.37, P < 0.001) width.

Table 4.25 Superficial tibiotalar ligament (STTL) length, width and thickness.

STTL Dimension		**N**	**Mean ± SD (mm)**
Length	**Neutral**	49	23.08 ± 3.75
Width	**Proximal**	56	5.23 ± 4.41
	Middle	44	5.06 ± 1.45
	Distal	54	5.66 ± 2.06
Thickness	**Middle**	45	0.89 ± 0.92

4.10.5 Change in Superficial Tibiotalar Ligament (STTL) Length

STTL length (Figure 4.48) in neutral was significantly different compared to its length in dorsiflexion (P < 0.001), plantarflexion (P < 0.001), inversion (P < 0.001) and eversion (P = 0.017). Moreover, there were significant differences in length between dorsiflexion and plantarflexion (P < 0.001), as well as between inversion and eversion (P < 0.001). Compared to STTL length in neutral (23.02 ± 3.8 mm), the ligament was significantly stretched in eversion (23.52 ± 4.28 mm) and dorsiflexion (24.22 ± 4.12 mm), but significantly shorter in plantarflexion (17.82 ± 3.81 mm) and inversion (17.95 ± 3.92 mm). STTL length in all joint positions showed no correlation with the PROM in maximum dorsiflexion, plantarflexion, inversion, eversion, isolated inversion or isolated eversion.

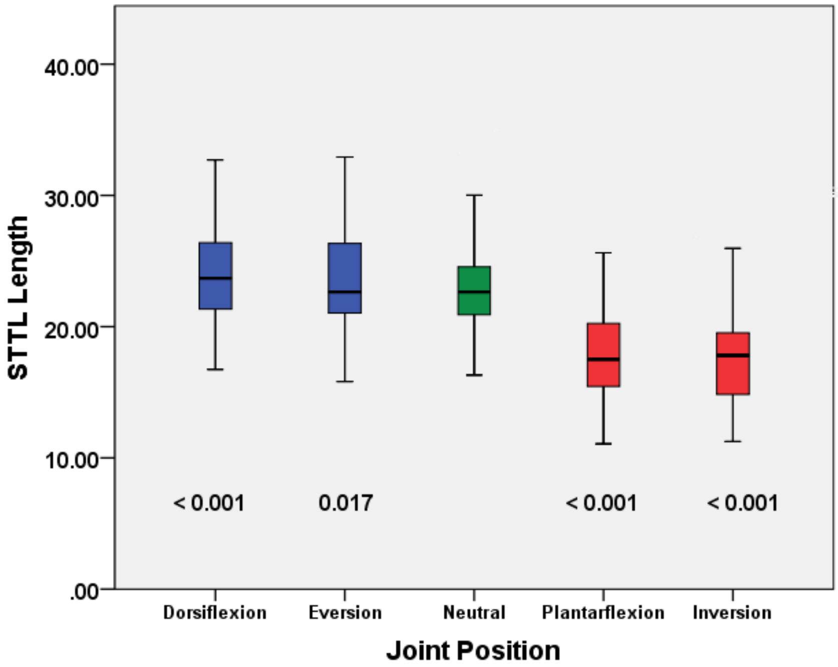

Figure 4.48 Change in the length of the superficial tibiotalar ligament (STTL) in dorsiflexion, eversion, plantarflexion and inversion compared to the neutral position.

4.10.6 Superficial Tibiotalar Ligament (STTL) Bony Attachment Lengths

The STTL had 17.52% of its length attached proximally to the medial malleolus, while 13.84% was attached distally (Table 4.26) leaving a free length of 68.65%. The STTL NBA was significantly different between genders: in males it was 18.5 ± 5.12 mm and in females 15.29 ± 4.27 mm. However, the STTL PBA and DBA did not differ between males and females. In addition, the STTL PBA, NBA and DBA showed no difference between right and left sides. STTL PBA was correlated with NBA ($r = -0.516$, $r^2 = 0.27$, $P = 0.001$) and STTL NBA with 1st metatarsal length ($r = 0.402$, $r^2 = 0.16$, $P = 0.015$), STTL length ($r = 0.644$, $r^2 = 0.41$, $P < 0.001$).

Table 4.26 Proximal (PBA) and distal (DBA) bony attachment lengths of the superficial tibiotalar ligament (STTL) together with the free ligament length (NBA): DF, dorsiflexion.

	N	**Mean** ± SD **(mm)**	**% of total length (DF)**
STTL PBA	37	4.28 ± 3.73	17.52%
STTL NBA	37	16.77 ± 4.89	68.65%
STTL DBA	37	3.38 ± 2.29	13.84%

4.11 Posterior Tibiotalar Ligament (PTTL)

The posterior tibiotalar ligament (PTTL) was a consistent and the largest part of the deep component of the deltoid ligament. It had wide attachment areas to the intercollicular groove (proximally) and the medial surface of the talus inferior to the malleolar articular surface (distally).

4.11.1 Band Number of the Posterior Tibiotalar Ligament (PTTL)

The posterior tibiotalar ligament was variably composed of one (8.1%), two (45.2%), three (45.2%) or four (2%, 1 specimen) bands (Figure 4.49). The one band form (Figure 4.50) was always seen unilaterally, while the two (Figure 4.51) and three (Figure 4.52) band forms were seen unilaterally in 46.15% and 45.45% of specimens respectively.

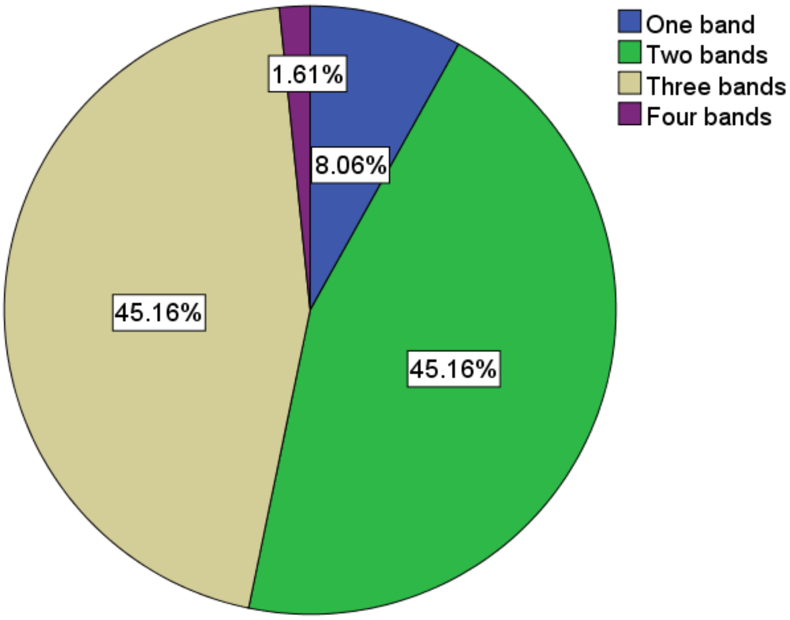

Figure 4.49 Band number of the deep posterior tibiotalar ligament (PTTL).

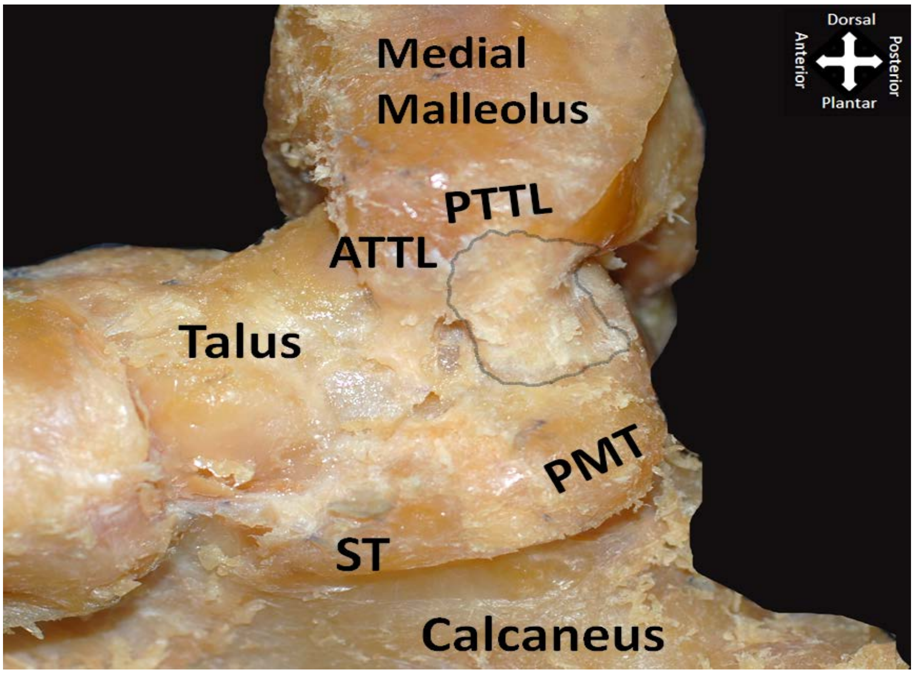

Figure 4.50 One band form of the posterior tibiotalar ligament (PTTL): ATTL, anterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

Male specimens had two and three bands in 43.5% and 56.5% respectively, while females had one (12.8%), two (46.2%), three (38.5%) or four (2.6%) band forms; analysis showed no significant difference between males and females. In addition, no difference in PTTL band number was observed between right and left sides: right side specimens had one (9.7%), two (48.4%), three (38.7%) and four (3.2%) bands, while the left side had one (6.5%), two (41.9%) and three (51.6%) bands.

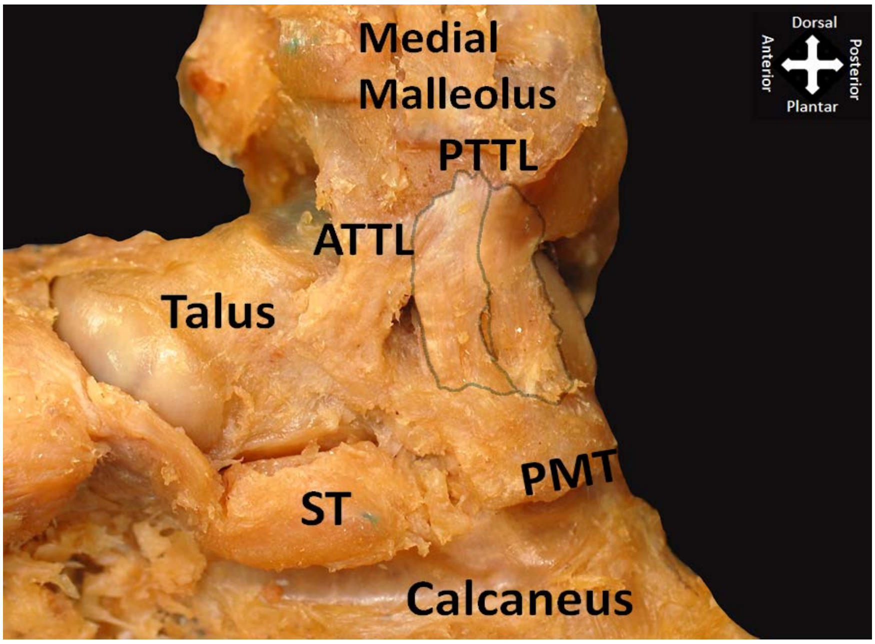

Figure 4.51 Two bands form of the posterior tibiotalar ligament (PTTL): ATTL, tibiotalar ligament; PMT, posteromedial tubercle; ST, sustentaculum tali.

PTTL band number did not differ with age, foot length or 1st metatarsal length. Isolated subtalar inversion PROM was significantly different in different PTTL band forms (P = 0.016), being 13° ± 5°, 12° ± 4° and 11° ± 4° in the one, two and three band forms. However, other PROMs in other joint positions did not differ with respect to the number of bands. The different bands in a multiband

PTTL were referred to as the anterior (APTTL) and posterior (PPTTL) bands of the PTTL in the two, three and four band forms; while the middle band was referred to as the MPTTL when it existed. Additionally, the APTTL was considered as the most anterior band in all forms; the one band form was also refered to as the APTTL in order to compare it to the anterior band in the other forms.

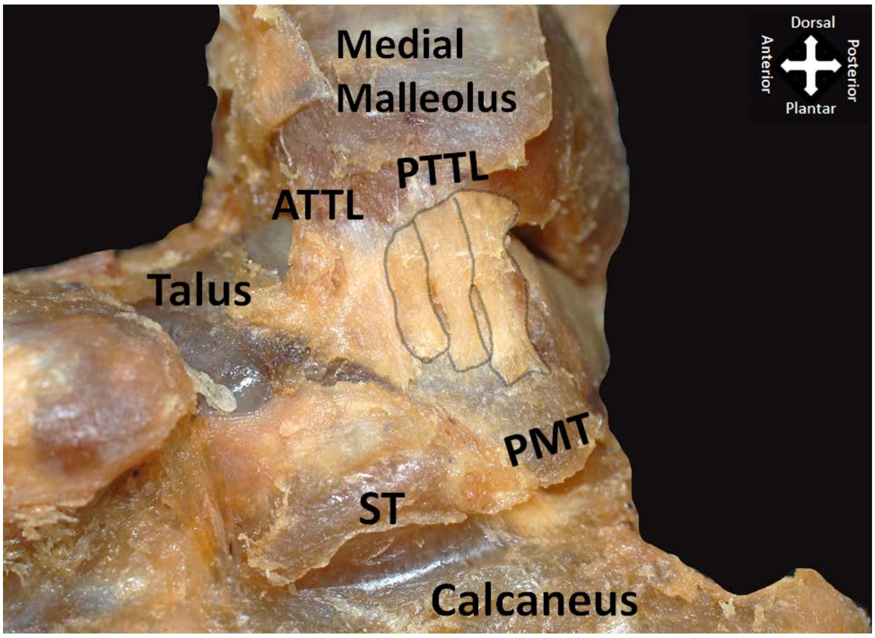

Figure 4.52 Three band form of the posterior tibiotalar ligament (PPTL): ATTL, anterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

4.11.2 Ligaments Superficial to the Posterior Tibiotalar Ligament (PTTL)

Ligaments superficial to the different parts of the PTTL are shown in Table 4.27. The APTTL was deep to the TCL and STTL (40.9%) and TCL (20.5%): other ligaments covering the APTTL are shown in Table 4.27. The STTL completely and partially covered the MPTTL in 54.5% and 9.1% of specimens respectively, while the TCL and STTL were superficial to the MPTTL in 22.7% of specimens:

other ligaments superficial to the MPTTL are shown in Table 4.27. The PPTTL was partially covered by the STTL in more than half of specimens (54.5%), while no ligaments were superficial to the PPTTL in 29.5%. Ligaments covering the APTTL, MPTTL and PPTTL were not significantly different between males and females or between right and left sides.

Table 4.27 Ligaments superficial to anterior (APTTL), middle (MPTTL) and posterior (PPTTL) bands of the deep posterior tibiotalar ligament: TSL, tibiospring ligament; TCL, tibiocalcaneal ligament; STTL, superficial tibiotalar ligament.

APTTL deeper to:	**Occurrence %**	**MPTTL deeper to:**	**Occurrence %**	**PPTTL deeper to:**	**Occurrence %**
TSL, TCL	13.60%	TCL, STTL	22.70%	STTL (partially)	54.50%
TSL, TCL, STTL	4.50%	STTL	54.50%	STTL	4.50%
STTL	9.10%	TSL, TCL, STTL	9.10%	TSL, TCL, STTL	2.30%
TCL, ATTL (partially)	2.30%	TSL, TCL, STTL, APTTL	4.50%	STTL (partially), PTTL (partially)	2.30%
TCL	20.50%	STTL (partially)	9.10%	TCL, STTL	2.30%
TCL, STTL	40.90%			MPTTL (partially)	2.30%
TCL, STTL, PPTL (partially)	2.30%			APTTL (partially)	2.30%
STTL (partially)	2.30%			None	29.50%
TSL (partially), TCL (partially)	2.30%				
TCL, STTL (partially)	2.30%				

4.11.3 Proximal Attachment of the Posterior Tibiotalar Ligament (PTTL)

The PTTL attached proximally to the medial malleolus (Figure 4.53), with different parts of the PTTL filling the intercollicular groove of the medial malleolus proximally (Figure 4.54): exact attachment points are shown in Table

4.28. These differences in the proximal attachment of the different PTTL bands showed no difference between males and females or between right and left sides.

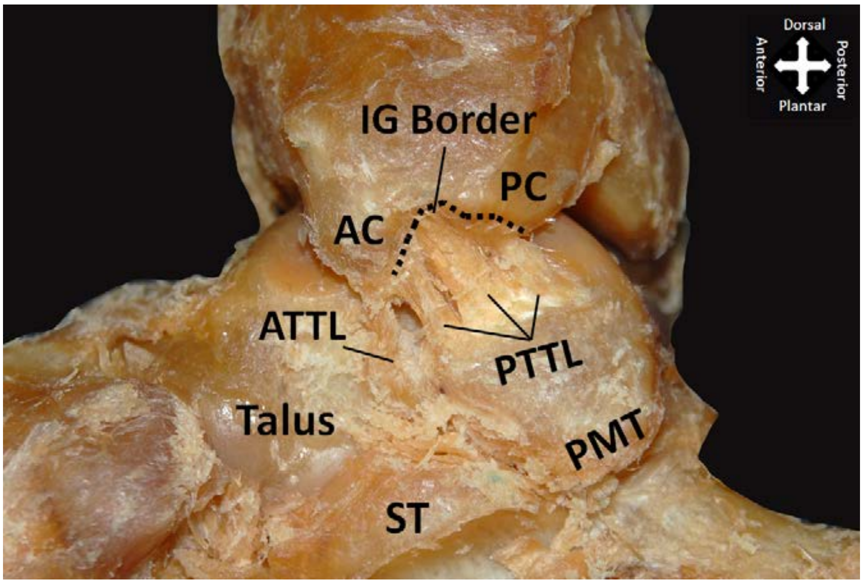

Figure 4.53 Proximal attachment of the posterior tibiotalar ligament (PTTL) between the anterior (AC) and posterior (PC) colliculi of the medial malleolus: ATTL, anterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

Table 4.28 Proximal attachment areas of the anterior (APTTL), middle (MPTTL) and posterior (PPTTL) bands of the posterior tibiotalar ligament (PTTL).

	Proximal Attachment	**Occurrence %**
APTTL	Posterior part of the anterior colliculus and the intercollicular groove	85.70%
	Posterior part of the anterior colliculus	7.10%
	Posterior part of the anterior colliculus, intercollicular groove and anterior part of the posterior colliculus	5.40%
	Medial surface of anterior colliculus, intercollicular groove and anterior part of posterior colliculus	1.80%
MPTTL	Intercollicular groove	91.70%
	Intercollicular groove and posterior part of the anterior colliculus	8.30%
PPTTL	Intercollicular groove and anterior part of the posterior colliculus	95.90%
	Posterior part of the anterior colliculus, intercollicular groove and anterior part of the posterior colliculus	2%
	Intercollicular groove, 3.1 mm superior to the border of the intercollicular groove and anterior part of the posterior colliculus	2%

A significant difference ($P < 0.001$) was noted between the APTTL proximal attachment and the different band forms. In the one band form the PTTL (APTTL) originated from the posterior part of the anterior colliculus, intercollicular groove and anterior part of the posterior colliculus filling all the intercollicular groove in 60% of specimens, or from the posterior part of the anterior colliculus and the intercollicular groove (20%), or from the medial surface of the anterior colliculus, intercollicular groove and anterior part of the posterior colliculus (20%). In the two band form, the APTTL attached proximally to either the posterior part of the anterior colliculus and the intercollicular groove (92.6%) or the posterior part of the anterior colliculus (7.4%). Similarly, in the three band form the APTTL originated from the posterior part of the anterior colliculus and intercollicular groove (91.7%) or from the posterior part of the anterior colliculus only (8.3%).

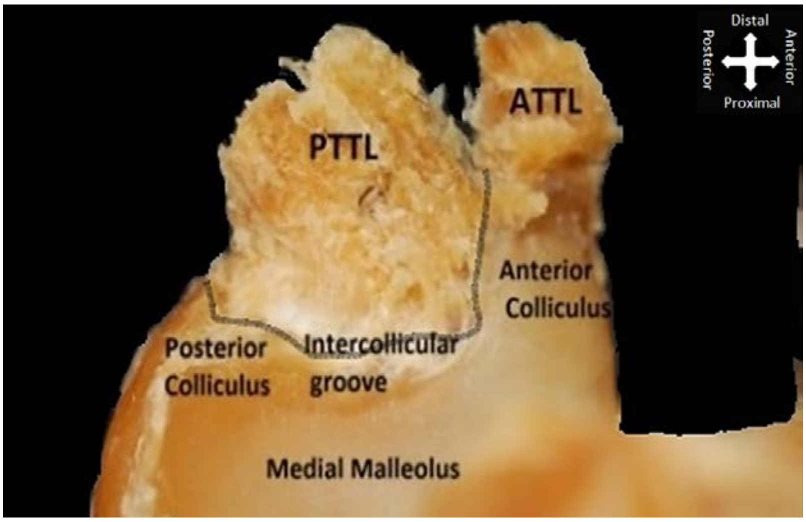

Figure 4.54 Proximal attachment of the posterior (PTTL) and anterior (ATTL) tibiotalar ligaments: A, anterior band of the PTTL; M, middle band of the PTTL; P, posterior band of the PTTL

On the other hand, the PPTTL proximal attachment was not significantly different in the different band forms. In the two band form, the majority of specimens (92%) had the PPTTL attaching proximally to the intercollicular groove and the anterior part of the posterior colliculus: other sites of attachment were the posterior part of the anterior colliculus, the intercollicular groove and anterior part of the posterior colliculus (4%), or the intercollicular groove 3.1 mm superior to its border and anterior part of the posterior colliculus (4%). The PPTTL in the three band form was always proximally attached to the intercollicular groove and the anterior part of the posterior colliculus.

4.11.4 Distal Attachment of the Posterior Tibiotalar Ligament (PTTL)

The different parts of the PTTL attached distally to the medial surface of the talus just inferior to the malleolar articular surface (Figure 4.55). In most cases (96.4%), the APTTL inserted into the talar medial surface being anterosuperior to the talar posteromedial tubercle. In one specimen it inserted posterosuperior to the posteromedial tubercle, while in another it inserted anterosuperior to the posteromedial tubercle as well as into the anterior border of the tubercle (one band form of PTTL). The MPTTL attached distally anterosuperior or posterosuperior to the posteromedial tubercle in 95.8% and 4.2% of specimens respectively. In 51.9% the PPTTL attached distally anterosuperior to the posteromedial tubercle, while in 46.2% it attached posterosuperior to posteromedial tubercle. In one specimen with two bands the PPTTL had a distal attachment anterosuperior to the posteromedial tubercle as well as to the anterior border of the posteromedial tubercle.

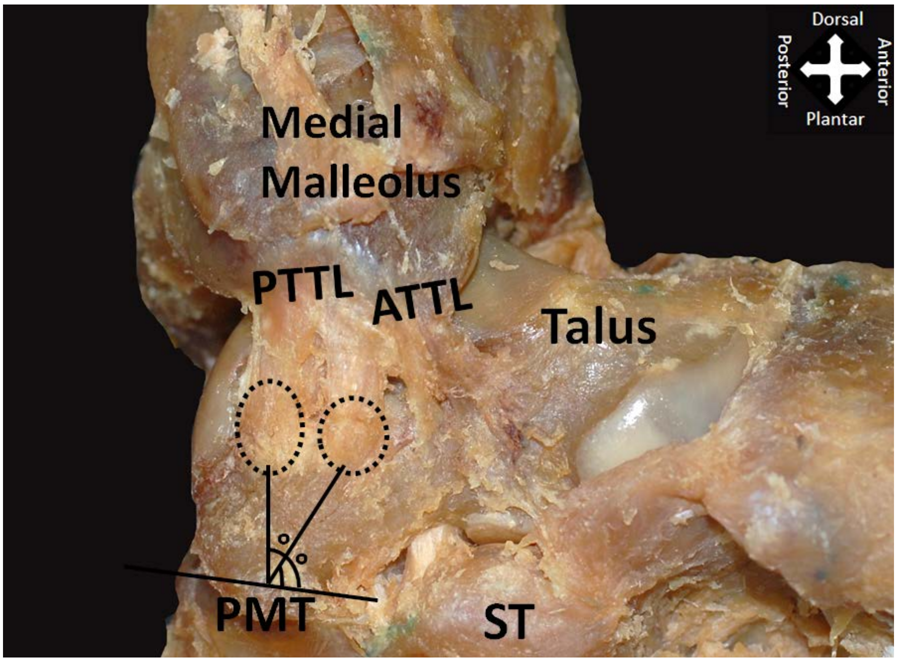

Figure 4.55 Distal attachment of the posterior tibiotalar ligament (PTTL) (dotted circle): the figure shows how the distance and angle between the distal attachment of the PTTL and the posteromedial tubercle (PMT) were measured; ATTL, anterior tibiotalar ligament; ST, sustentaculum tali.

The distal attachments of the different parts of the PTTL were not significantly different between males and females or between right and left sides. However, the APTTL distal attachment was significantly different in the different PTTL band forms (P = 0.010). The APTTL distal attachment was anterosuperior to the posteromedial tubercle in the one, two, three and four band forms in 60%, 100%, 100% and 100% respectively, with the APTTL distal insertion only being observed posterosuperior to the posteromedial tubercle in the one band form in 20% of specimens. In addition, the band inserted distally anterosuperiorly and to the border of the posteromedial tubercle in 20% of specimens in the one band form. There were no significant differences in the PPTTL distal attachments. The two band form had a distal attachment anterosuperior (55.6%) or posterosuperior (40.7%) to the posteromedial tubercle, while in 3.7%

it inserted anterosuperior and to the border of the posteromedial tubercle. The PPTTL distal attachment was either anterosuperior (50%) or posterosuperior (50%) to the posteromedial tubercle.

The distance and angle between the distal attachments of the different bands of the PTTL and the talar posteromedial tubercle are shown in Table 4.29. A significant difference in the distance between the APTTL distal attachment and the posteromedial tubercle between males and females (P = 0.034) was observed, being 11.41 ± 3.1 mm in males and 9.44 ± 3.36 mm in females. The MPTTL distance to the posteromedial tubercle was also significantly greater (P = 0.024) in males (9.23 ± 1.49 mm) compared to females (7.54 ± 1.91 mm). However, other distances and angles between the different PTTL bands distal attachments and the talar posteromedial tubercle did not differ between genders. The angle between the MPTTL distal insertion and the posteromedial tubercle was significantly different between right and left sides (P = 0.003), with the angle on the right being 43° ± 14° and on the left 66° ± 18°. Other distances and angles did not differ between right and left feet.

Table 4.29 Distance and angle between the distal site of attachment of the anterior (APTTL), middle (MPTTL) and posterior (PPTTL) bands of the deep posterior tibiotalar ligament (PTTL) and the posteromedial tubercle (PMT).

PTTL Band	Distance to the PMT (mm)	Angle with the PMT
APTTL	10.19 ± 3.37	41° ± 18°
MPTTL	8.39 ± 1.88	56° ± 20°
PPTTL	7.29 ± 2.34	87° ± 19°

Significant differences in the distance (P = 0.003) and angle (P = 0.001) between the APTTL distal attachment and the posteromedial tubercle in the different band forms of the PTTL were observed. In the one band form the distance was 5.55 ± 0.77 mm, in the two band form 9.94 ± 3.36 mm, in the three band form 11.5 ± 3.02 mm and in the four band form 9.83 mm. The angle between the APTTL distal attachment and the posteromedial tubercle was 65° ± 33° (one band), 45° ± 14°, 33° (two bands), 33° ± 13° (three bands) and 22° (four bands).

A significant correlation (Table 4.30) between the APTTL distal attachment distance to the posteromedial tubercle and foot length, 1st metatarsal length, age, distal width and the distal attachment angle to the posteromedial tubercle was found, as well as between The angle with 1st metatarsal length, APTTL distal width and APTTL distal attachment distance to posteromedial tubercle.

There were significant correlations (Table 4.30) between the MPTTL distal attachment distance to the posteromedial tubercle and age and foot length, and between the angle between the MPTTL distal attachment and posteromedial tubercle and MPTTL distal width. A significant correlation between the PPTL distal attachment distance to the posteromedial tubercle and age was observed.

Table 4.30 Significant correlations between the distance and angle between the posteromedial tubercle (PMT) and the distal attachment of the anterior (APTTL), middle (MPTTL) and posterior (PPTTL) bands of the deep posterior tibiotalar ligament (PTTL).

	Correlation with	**N**	**Correlation Coefficient (r)**	**r^2**	**P Value**
Distance between APTTL distal attachment and PMT	Age	55	- 0.489	0.24	< 0.001
	Foot Length	52	0.436	0.19	0.001
	1st metatarsal length	53	0.352	0.12	0.01
	APTTL Distal Width	55	- 0.325	0.11	0.016
	APTTL distal attachment angle with PMT	55	- 0.537	0.29	< 0.001
Angle between APTTL distal attachment and PMT	1st metatarsal length	53	- 0.303	0.09	0.027
	APTTL Distal Width	55	0.289	0.08	0.032
	APTTL distal attachment distance to PMT	55	- 0.537	0.29	< 0.001
Distance between MPTTL distal attachment and PMT	Age	24	- 0.662	0.44	< 0.001
	Foot Length	23	0.553	0.31	0.006
Angle between MPTTL distal attachment and PMT	MPTTL Distal Width	23	0.440	0.19	0.036
Distance between PPTTL distal attachment and PMT	Age	51	- 0.278	0.08	0.048

4.11.5 Posterior Tibiotalar Ligament (PTTL) Orientation

The APTTL was similarly orientated (Figures 4.56 and 4.57) posteroinferiorly and inferiorly in neutral (88.9% and 11.1%) and dorsiflexion (81.5% and 18.5%). Only a posteroinferior orientation was seen in plantarflexion and inversion, while in eversion the APTTL had posteroinferior and inferior orientations in 80% and 20% of specimens respectively. In neutral the MPTTL had posteroinferior, inferior and anteroinferior orientations in 81.8%, 9.1% and 9.1% respectively, while in dorsiflexion it was oriented posteroinferiorly (54.5%) and inferiorly (45.5%). A posteroinferior orientation of the MPTTL was always observed in plantarflexion and inversion, while it had posteroinferior (70%) and inferior (30%) orientations in eversion. On the other hand, the PPTTL was orientated posteroinferiorly in all joint positions. There was no association between the APTTL and MPTTL orientations in any joint positions or with PTTL band number.

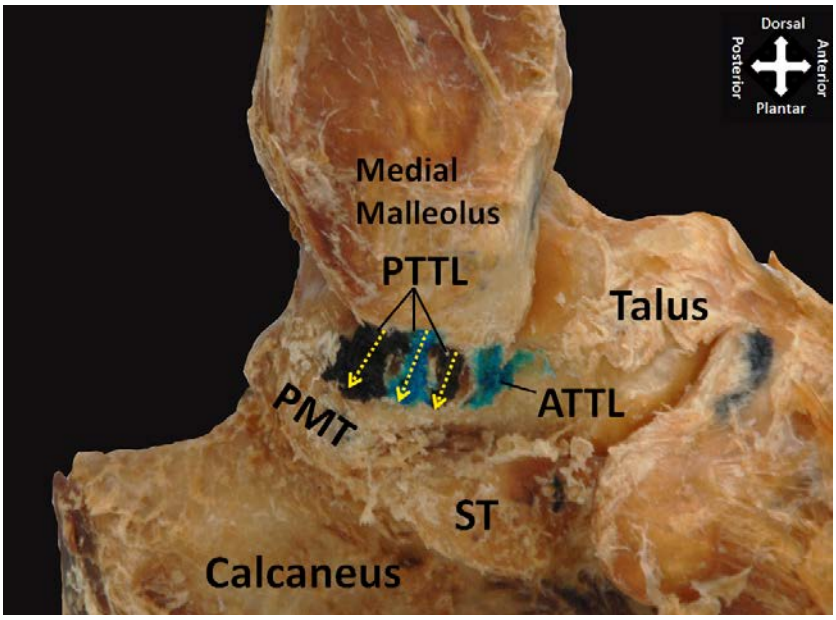

Figure 4.56 Posteroinferior orientation (yellow dotted arrows) of the different parts of the posterior tibiotalar ligament (PTTL): ATTL, anterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

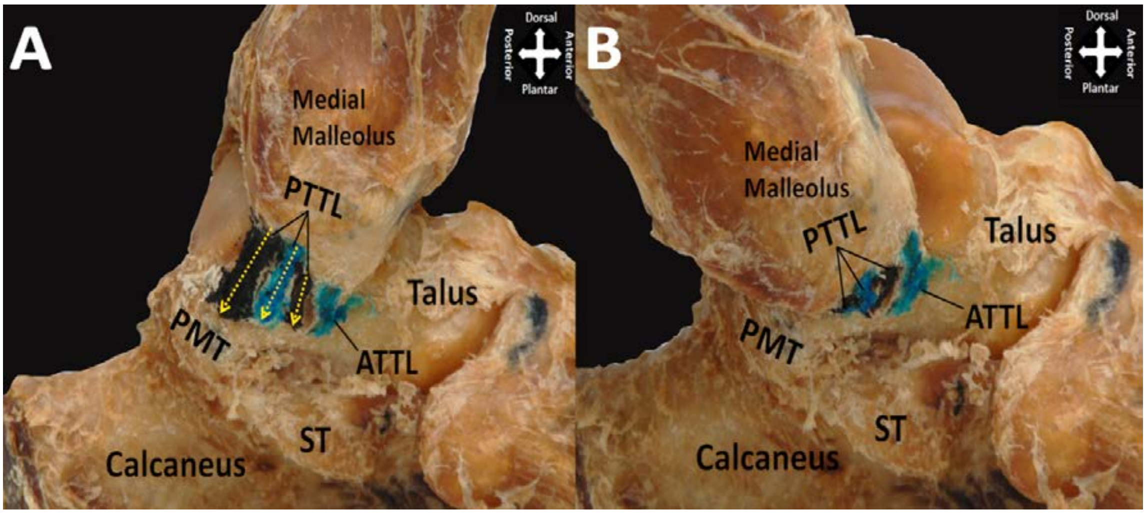

Figure 4.57 Orientation (yellow dotted arrows) of the different parts of the posterior tibiotalar ligament (PTTL) in dorsiflexion (A) and plantarflexion (B) (the orientation was not highlighted in plantarflexion as the ligament was slack and folded in this position): ATTL, anterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

4.11.6 Posterior Tibiotalar Ligament (PTTL) Dimensions

The APTTL had a length, mid width and thickness of 14.89 ± 4.02 mm, 3.98 ± 2.15 mm and 1.46 ± 0.76 mm respectively (Table 4.31). MPTTL dimensions were 15.8 ± 3.8 mm (length), 2.84 ± 1.06 mm (mid width) and 0.85 ± 0.39 mm (thickness). The PPTTL was 15.2 ± 3.92 mm, 4.55 ± 1.52 and 1.53 ± 0.61 mm in length, mid width and thickness respectively (Table 4.31). The total width of the PTTL was 10.08 ± 2.75 mm (proximally), 9.43 ± 1.92 mm (mid) and 11.87 ± 2.45 mm (distally). There were no differences in PTTL dimensions between right and left sides.

Table 4.31 Dimensions of the anterior (APTTL), middle (MPTTL) and posterior (PPTTL) bands of the deep posterior tibiotalar ligament (PTTL).

		APTTL (N)	Mean ± SD (mm)	MPTTL (N)	Mean ± SD (mm)	PPTTL (N)	Mean ± SD (mm)
Length	**Neutral**	51	14.89 ± 4.02	22	15.8 ± 3.8	47	15.2 ± 3.92
Width	**Proximal**	60	3.94 ± 2.13	26	3.5 ± 1.48	55	4.92 ± 1.85
	Middle	52	3.98 ± 2.15	25	2.84 ± 1.06	49	4.55 ± 1.52
	Distal	60	4.83 ± 2.61	27	3.33 ± 0.99	56	5.95 ± 2.04
Thickness	**Middle**	51	1.46 ± 0.76	19	0.85 ± 0.39	45	1.53 ± 0.61
Total	**Proximal**	58	10.08 ± 2.75				
Width	**Middle**	51	9.43 ± 1.92				
	Distal	58	11.87 ± 2.45				

APTTL length was significantly different between genders (P <0.001), being 17.43 ± 3.7 mm in males and 13.11 ± 3.2 mm in females. Similarly, there were significant differences in PPTTL length (P = 0.003) and thickness (P = 0.049) between males and females, with length and thickness in males being 17.06 ± 4 mm and 1.72 ± 0.71 mm and in females 13.71 ± 3.19 mm and 1.36 ± 0.46 mm. In addition, the total mid width of the PTTL was also significantly different between genders (P = 0.013), being 10.22 ± 1.61 mm in males and 8.88 ± 1.96 mm in females. However, there were no differences in other PTTL dimensions between males and females.

Compared to the total mid width there were significant differences with total proximal (P = 0.045) and total distal (P < 0.001) widths. Additionally, there was a significant difference in the total distal width (P < 0.001) compared to the total proximal width. A significant difference in the thickness of the APTTL (P = 0.031) and PPTTL (P = 0.028) compared to the MPTTL was observed, but there were no differences in the thickness of the APTT and PPTTL. This shows that the APTTL and PPTTL thickness were significantly greater than the MPTTL.

Differences in the dimensions of the PTTL with respect to the different PTTL band forms are shown in Table 4.32. APTTL and PPTTL lengths did not differ irrespective of band number. However, the proximal, mid and distal widths were significantly different (P < 0.001) in the different band forms: APTTL width was significantly wider. In addition, the PPTTL mid and distal widths were significantly different in the different band forms, but not the proximal width. The mid and distal PPTTL were wider in the two band form compared to the three band form. APTTL and PPTTL thickness in the different PTTL band forms did not differ. Finally, analysis showed that the total mid and distal widths did not differ between PTTL band number. However, the total proximal width was significantly different with respect to the band number.

Table 4.32 Dimensions of the anterior (APTTL) and posterior (PPTTL) bands of the deep posterior tibiotalar ligament (mean ± SD (mm) in different band forms.

Dimension	One Band	Two Bands	Three Bands	Four Bands	P Value
APTTL Length	15.75 ± 3.19	15.16 ± 4.41	14.62 ± 3.84	10.31	0.641
PPTTL Length		15.98 ± 3.93	14.53 ± 3.92	12.94	0.395
APTTL Proximal Width	8.98 ± 3.53	3.81 ± 1.37	3.2 ± 0.96	2.01	< 0.001
APTTL Middle Width	8.96 ± 2.41	3.77 ± 1.5	3.21 ± 0.96	1.74	< 0.001
APTTL Distal Width	11.38 ± 4.24	4.64 ± 1.24	3.92 ± 1.3	2.02	< 0.001
PPTTL Proximal Width		5.36 ± 1.87	4.43 ± 1.74	6.41	0.127
PPTTL Middle Width		5.25 ± 1.39	3.94 ± 1.39	3.71	0.007
PPTTL Distal Width		6.82 ± 1.97	5 ± 1.74	7.02	0.002
APTTL Thickness	1.96 ± 0.63	1.62 ± 0.72	1.24 ± 0.75	0.37	0.067
PPTTL Thickness		1.68 ± 0.57	1.37 ± 0.64	1.57	0.254
PTTL Total Proximal Width	8.98 ± 3.53	9.17 ± 2.09	11.16 ± 2.89	13.29	0.026
PTTL Total Middle Width	8.96 ± 2.41	9.01 ± 1.75	9.92 ± 1.99	10.42	0.391
PTTL Total Distal Width	11.38 ± 4.24	11.33 ± 1.95	12.43 ± 2.46	15.02	0.216

Tables 4.33 and 4.34 show the significant correlations between the dimensions of the different bands of the PTTL and a number of factors. APTTL length was positively correlated with foot length, 1st metatarsal length, all widths and PPTTL length, and APTTL proximal width with length, mid and distal width. In addition, positive correlations were observed between mid width and length, and proximal and distal width, and between APTTL distal width and length, proximal width, mid width and DBA. APTTL thickness was correlated with MPTTL thickness.

MPTTL length was positively correlated with proximal width, distal width and PPTTL length, and MPTTL proximal width with length, mid and distal width. Positive correlations were also observed between the MPTTL mid width and length, proximal width, distal width and NBA, and distal width with proximal and mid width. There was also a correlation between MPTTL thickness and APTTL thickness.

PPTTL length was correlated with 1st metatarsal length, proximal width, thickness, APTTL length and MPTTL length, and PPTTL proximal width with PPTTL length, mid and distal width and thickness. PPTTL mid width was also correlated with 1st metatarsal length, proximal width, distal width and thickness, while PPTTL distal width was correlated with proximal and mid width. PPTTL thickness was correlated with length, the proximal and mid width. PTTL total proximal width was correlated with the total mid and total distal width, and PTTL total mid width with age, foot length, 1st metatarsal length, total proximal and total distal width. PTTL total distal width was also correlated with age, foot length, 1st metatarsal length, total proximal and total mid width.

Table 4.33 Significant correlations between the dimensions of the anterior (APTTL), middle (MPTTL) and posterior (PPTTL) bands of the deep posterior tibiotalar ligament (PTTL) and other parameters and factors.

PTTL Dimension	Correlation with	N	Correlation coefficient (r)	r^2	P Value
APTTL length	Foot Length	50	0.423	0.18	0.002
	1st Metatarsal Length	50	0.471	0.22	0.001
	APTTL Proximal Width	51	0.278	0.08	0.048
	APTTL Middle Width	50	0.437	0.19	0.001
	APTTL Distal Width	51	0.337	0.11	0.015
	PPTTL Length	45	0.669	0.45	< 0.001
APTTL Proximal Width	APTTL Length	51	0.278	0.08	0.048
	APTTL Middle Width	52	0.772	0.6	< 0.001
	APTTL Distal Width	59	0.836	0.7	< 0.001
APTTL Middle Width	APTTL length	50	0.437	0.19	0.001
	APTTL Proximal Width	52	0.772	0.6	< 0.001
	APTTL Distal Width	52	0.918	0.84	< 0.001
APTTL Distal Width	APTTL Length	51	0.337	0.11	0.015
	APTTL Proximal Width	59	0.836	0.7	< 0.001
	APTTL Middle Width	52	0.918	0.84	< 0.001
	APTTL DBA	40	0.450	0.2	0.004
APTTL Thickness	MPTTL Thickness	18	0.492	0.24	0.038
MPTTL Length	MPTTL Proximal Width	22	0.564	0.32	0.006
	MPTTL Middle Width	22	0.533	0.28	0.011
	PPTTL Length	21	0.652	0.43	< 0.001

MPTTL Proximal Width	MPTTL Length	22	0.564	0.32	0.006
	MPTTL Middle Width	24	0.706	0.5	< 0.001
	MPTTL Distal Width	25	0.629	0.4	0.001
MPTTL Middle Width	MPTTL Length	22	0.533	0.28	0.011
	MPTTL Proximal Width	24	0.706	0.5	< 0.001
	MPTTL Distal Width	25	0.629	0.4	0.001
	MPTTL NBA	15	0.515	0.27	0.05
MPTTL Distal Width	MPTTL Proximal Width	25	0.629	0.4	0.001
	MPTTL Middle Width	25	0.629	0.4	0.001
MPTTL Thickness	APTTL Thickness	18	0.492	0.24	0.038
PPTTL Length	1st Metatarsal Length	46	0.292	0.09	0.049
	PPTTL Proximal Width	47	0.341	0.12	0.019
	PPTTL Thickness	44	0.652	0.43	< 0.001
	APTTL Length	45	0.669	0.45	< 0.001
	MPTTL Length	21	0.652	0.43	< 0.001
PPTTL Proximal Width	PPTTL Length	47	0.341	0.12	0.019
	PPTTL Middle Width	49	0.574	0.33	< 0.001
	PPTTL Distal Width	55	0.474	0.22	< 0.001
	PPTTL Thickness	45	0.344	0.12	0.021
PPTTL Middle Width	1st Metatarsal Length	47	0.303	0.09	0.037
	PPTTL Proximal Width	49	0.574	0.33	< 0.001
	PPTTL Distal Width	45	0.736	0.54	< 0.001
	PPTTL Thickness	45	0.319	0.10	0.033
PPTTL Distal Width	PPTTL Proximal Width	55	0.474	0.22	< 0.001
	PPTTL Middle Width	45	0.736	0.54	< 0.001
PPTTL Thickness	PPTTL Length	44	0.652	0.43	< 0.001
	PPTTL Proximal Width	45	0.344	0.12	0.021
	PPTTL Middle Width	45	0.319	0.10	0.033

Table 4.34 Significant correlations between deep posterior tibiotalar ligament (PTTL) total width and other parameters and factors.

PTTL Dimension	Correlation with	N	Correlation coefficient (r)	r^2	P Value
PTTL Total Proximal Width	PTTL Total Middle Width	50	0.641	0.41	< 0.001
	PTTL Total Distal Width	57	0.705	0.5	< 0.001
PTTL Total Middle Width	Age	51	- 0.298	0.09	0.033
	Foot Length	49	0.446	0.2	0.001
	1st Metatarsal Length	49	0.373	0.14	0.008
	PTTL Total Proximal Width	50	0.641	0.41	< 0.001
	PTTL Total Distal Width	51	0.669	0.45	< 0.001
PTTL Total Distal Width	Age	58	- 0.375	0.14	0.004
	Foot Length	55	0.399	0.16	0.003
	1st Metatarsal Length	56	0.330	0.11	0.013
	PTTL Total Proximal Width	57	0.705	0.5	< 0.001
	PTTL Total Middle Width	51	0.669	0.45	< 0.001

4.11.7 Change in the Posterior Tibiotalar Ligament (PTTL) length

APTTL length in neutral (15.01 ± 4.11 mm) was significantly different (Figure 4.58) to that in plantarflexion (11.74 ± 3.33 mm), dorsiflexion (15.67 ± 3.88 mm) and inversion (11.75 ± 3.29 mm), but not to that in eversion (15.18 ± 3.74 mm). In addition, a significant difference was observed between dorsiflexion and plantarflexion ($P < 0.001$) and between inversion and eversion ($P < 0.001$). This shows that APTTL length in plantarflexion and inversion were significantly shorter compared to neutral, while in dorsiflexion it was longer. Moreover, in dorsiflexion the APTTL becomes significantly stretched compared to that in plantarflexion, in which the ligament was less stressed. In addition, it was significantly shorter in inversion compared to eversion. There were no correlations between the change in APTTL length and all the applied maximum PROMs.

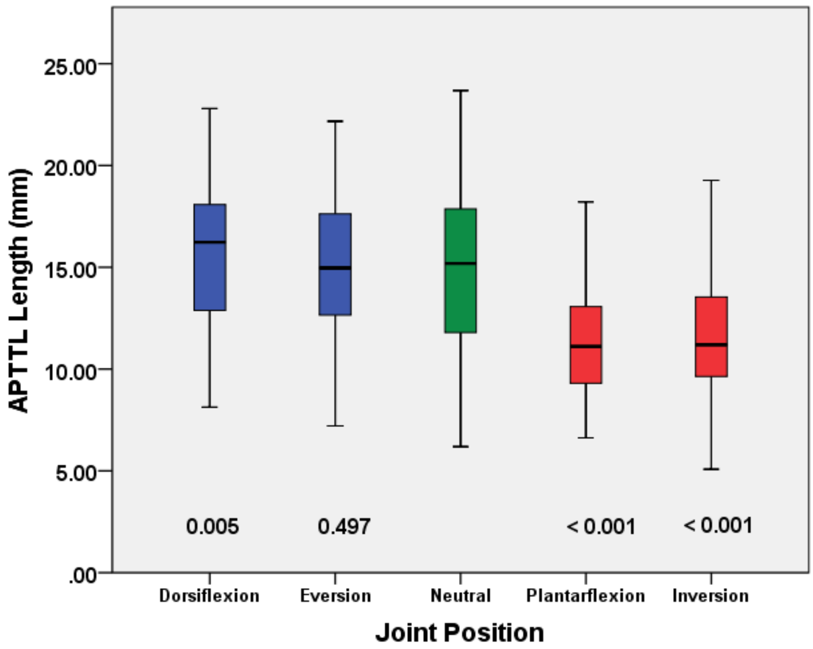

Figure 4.58 Change in the anterior band of the posterior tibiotalar ligament (APTTL) length in different joint positions.

MPTTL length in neutral (15.56 ± 4.54 mm) was significantly different to its length in dorsiflexion (16.28 ± 4.78 mm; $P = 0.030$), plantarflexion (11.24 ± 4.32 mm; $P < 0.001$) and inversion (11.19 ± 4.12 mm; $P < 0.001$), but not in eversion (15.58 ± 4.4 mm). In addition, there were significant differences in length between dorsiflexion and plantarflexion ($P < 0.001$), as well as between inversion and eversion ($P < 0.001$). This shows that the MPTTL was most stretched in dorsiflexion and shortest in plantarflexion and inversion compared to neutral. In addition, the ligament showed that it was more taut in dorsiflexion than plantarflexion, as well as being more relaxed in inversion than in eversion. No correlation was found between the change in MPTTL length and the applied maximum PROMs.

PPTTL length in neutral (15.29 ± 4.17 mm) was significantly different ($P < 0.001$) compared to that in dorsiflexion (16.47 ± 3.94 mm), plantarflexion (10.7 ± 3.4 mm) and inversion (10.09 ± 3.04 mm), but not eversion (15.12 ± 3.59 mm). In addition, the length in dorsiflexion was significantly different compared to that in plantarflexion, while in inversion it was significantly different to that in eversion. This indicates that the PPTTL was more taut in dorsiflexion and more relaxed in plantarflexion and inversion. However, there was no correlation between the PPTTL lengths in different joint positions and the different applied PROMs.

4.11.8 Posterior Tibiotalar Ligament (PTTL) Bony Attachment Lengths

The APTTL had 27.9%, 51.46% and 21.15% of its length attached proximally to the tibia (proximal bony attachment; PBA), free length (no bony attachment; NBA) and attached distally the talus (distal bony attachment; DBA) respectively

(Table 4.35). The MPTTL had a PBA, NBA and DBA of 17.4%, 66.01% and 16.53% of its length respectively, while the bony attachment lengths of the PPTTL were 19.87% (PBA) and 31.05% (DBA), with 49.08% being free.

There was no difference in the PTTL bony attachment lengths between males and females, except for APTTL NBA (P = 0.029) and PPTTL DBA (P = 0.015). APTTL NBA was 9.14 ± 3.19 mm in males and 7.24 ± 1.52 mm in females, while PPTTL DBA was 6.07 ± 2.64 mm and 4.22 ± 2.14 mm in males and females respectively. No difference in the PTTL bony attachment lengths was observed between right and left sides.

Table 4.35 Bony attachment lengths of the anterior (APTTL), middle (MPTTL) and posterior (PPTTL) bands of the deep posterior tibiotalar ligament: PBA, proximal bony attachment length; NBA, no bony attachment length; DBA, distal bony attachment length.

		N	Mean ± SD (mm)	% of the total length (DF)
APTTL	**PBA**	41	4.38 ± 1.81	27.90%
	NBA	41	8.08 ± 2.55	51.46%
	DBA	40	3.32 ± 1.85	21.15%
MPTTL	**PBA**	15	2.82 ± 1.31	17.40%
	NBA	15	10.70 ± 3.96	66.01%
	DBA	15	2.68 ± 1.68	16.53%
PPTTL	**PBA**	43	3.25 ± 1.67	19.87%
	NBA	43	8.03 ± 2.38	49.08%
	DBA	43	5.08 ± 2.53	31.05%

There were correlations between APTTL NBA and foot length ($r = 0.427$, $r^2 = 0.18$, $P = 0.006$) and 1st metatarsal length ($r = 0.403$, $r^2 = 0.16$, $P = 0.01$), and between APTTL DBA and distal width ($r = 0.450$, $r^2 = 0.20$, $P = 0.004$). MPTTL PBA was correlated with DBA ($r = 0.615$, $r^2 = 0.38$, $P = 0.004$), while MPTTL NBA was correlated with mid width ($r = 0.515$, $r^2 = 0.27$, $P = 0.05$).

The PPTTL PBA was correlated with NBA ($r = -0.327$, $r^2 = 0.11$, $P = 0.033$), while PPTTL NBA was correlated with thickness ($r = 0.493$, $r^2 = 0.24$, $P = 0.001$) and PBA ($r = -0.327$, $r^2 = 0.11$, $P = 0.033$), and PPTTL DBA with thickness ($r = 0.514$, $r^2 = 0.26$, $P = 0.001$).

4.11.9 Middle Bands in the Four Band Form of the Posterior Tibiotalar Ligament (PTTL)

The four band form of the PTTL had two middle bands: superficial and deep (Figure 4.59). The superficial band had a length of 15.25 mm in neutral, 17.4 mm in dorsiflexion and 15.86 mm in eversion, while the proximal, mid and distal widths were 4.87 mm, 4.97 mm and 4.78 mm respectively and the mid thickness 0.76 mm. The PBA, NBA and DBA comprised 38.28%, 55.4% and 6.32% of the band length in dorsiflexion. The superficial band was deep to the STTL, originating from the posterior part of the anterior colliculus and intercollicular groove of the medial malleolus. It passed to insert distally to the medial surface of the talus anterosuperior to the posteromedial tubercle: the distance and angle between the mid distal attachments of the superficial band to the posteromedial tubercle were 9.83 mm and 53° respectively.

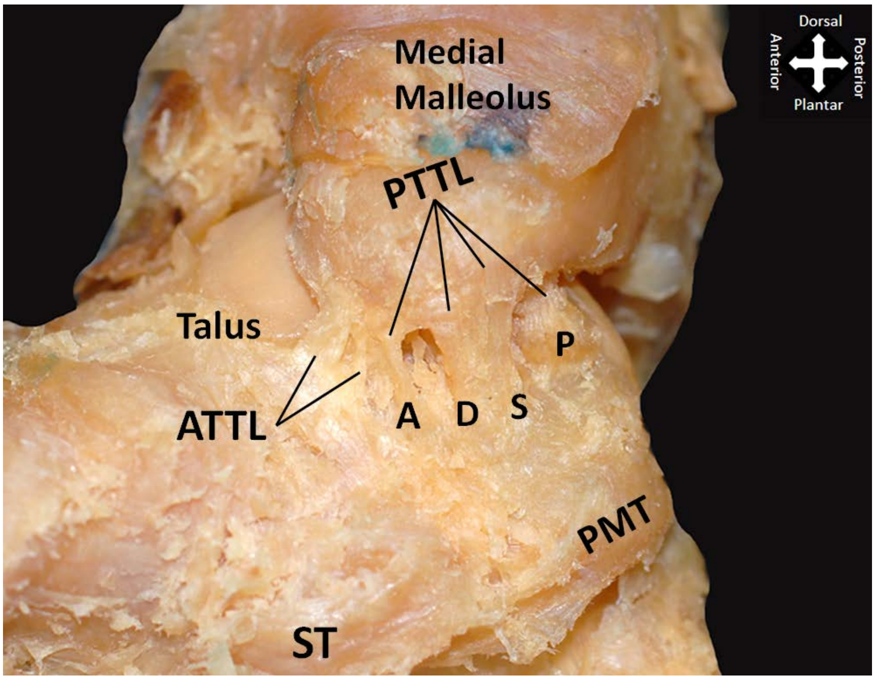

Figure 4.59 Four band form of the posterior tibiotalar ligament (PTTL) consisting of anterior (A), posterior (P), superficial middle (S) and deep middle (D) bands: ATTL, anterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

The deep band had a length of 9.84 mm, 8.22 mm and 9.56 mm in neutral, plantarflexion and eversion respectively. Its width was 3.16 mm proximally, 4.43 mm at the mid length and 5.98 mm distally. It was covered superficially by the MPTTL and originated from the intercollicular groove as well as the surface of the medial malleolus superior to the border of the intercollicular groove. Distally the ligament crossed to attach to the medial surface of the talus inferior to the malleolar articular surface and anterosuperior to the posteromedial tubercle: the distance and angle of the distal attachment to the posteromedial tubercle were 8.93 mm and 87° respectively.

4.11.10 Relations to Other Bands

Proximally the PTTL was clear from the ATTL in 20% of specimens, being separated from the ATTL proximally 6.26 ± 2.54 mm distal to the PTTL proximal attachment. In 68.75% of specimens the PTTL continued 3.55 ± 2.04 mm proximally free from the ATTL. In the two band form the APTTL separated from the PPTTL proximally 5.64 ± 3.04 mm, while in 21.88% of specimens the APTTL continued 1.31 ± 0.73 mm proximally free from the PPTTL. Distally the APTTL was completely clear of the PPTTL in 5.88%, while in the remainder the APTTL attached to the PPTTL distally and was separated 2.42 ± 1.46 mm proximal to the APTTL distal attachment: in 18.75% of these the APTTL extended 0.91 ± 0.54 mm distally free from the PPTTL.

In the three band form, the APTTL was not attached to the MPPTL proximally in 17.65%, while in the remainder it separated from the MPTTL proximally 5.57 ± 2.37 mm. In 14.29% the APTTL extended 3.12 ± 3.03 mm proximally free from the MPTTL. In 25%, the APTTL was completely clear of the MPTTL distally, but in the remaining specimens the APTTL attached to the MPTTL separating 3.74 ± 2.36 mm proximal to the APTTL distal attachment.

The MPTTL was continuous and completely clear proximally from the PPTTL in 6.67% and 6.67% of specimens respectively: in the remainder it attached to the PTTL proximally separating 7.73 ± 3.19 mm distal to the proximal attachment of the MPTTL: in 76.9% the MPTTL extended proximally with 2.13 ± 0.94 mm being free from the PPTTL. Distally, the MPTTL was continuous with the PPTTL in 11.11% and separated in the remaining specimens 2.71 ± 1.46 mm proximal to the distal attachment of the MPTTL: in one specimen the MPTTL extended 0.65 mm free distally.

4.12 Anterior Tibiotalar Ligament (ATTL)

The anterior tibiotalar ligament (ATTL) was observed in 96.7% of specimens. There was no difference in the presence of the ATTL between males and females or between right and left sides.

4.12.1 Band Number of the Anterior Tibiotalar Ligament (ATTL)

The ATTL had one (Figure 4.60) or two bands (Figure 4.61) in 70.7% and 29.3% of specimens respectively, with no difference between males and females or between right and left sides in band number. In addition, there was no difference in ATTL band number and age, foot length or 1st metatarsal length. The one band form was observed unilaterally in 29.4% of specimens and bilaterally in 70.59%, while the two band form was observed unilaterally and bilaterally in 60% and 40% respectively. Where two bands occurred they separated having different distal attachments and directions in many cases: they were referred to as the anterior (AATTL) and posterior (PATTL) bands of the anterior tibiotalar ligament (ATTL).

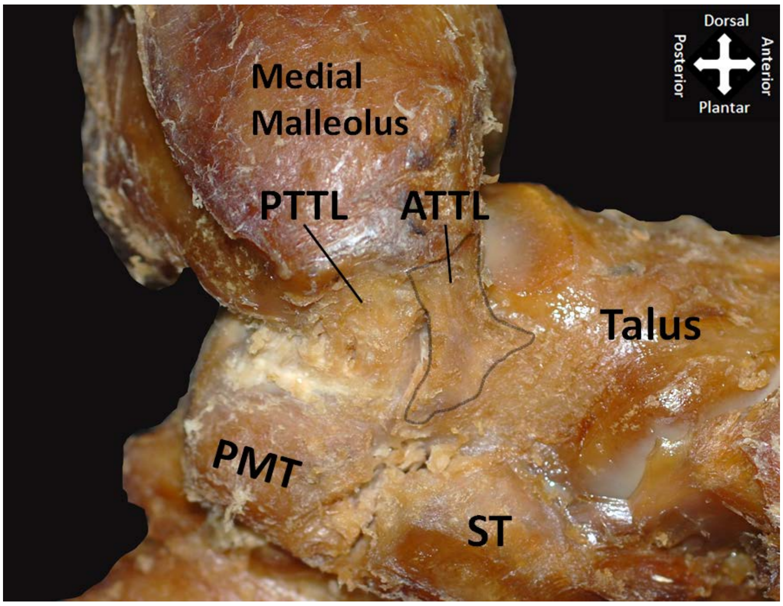

Figure 4.60 One band form of the anterior tibiotalar ligament (ATTL): PTTL, posterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

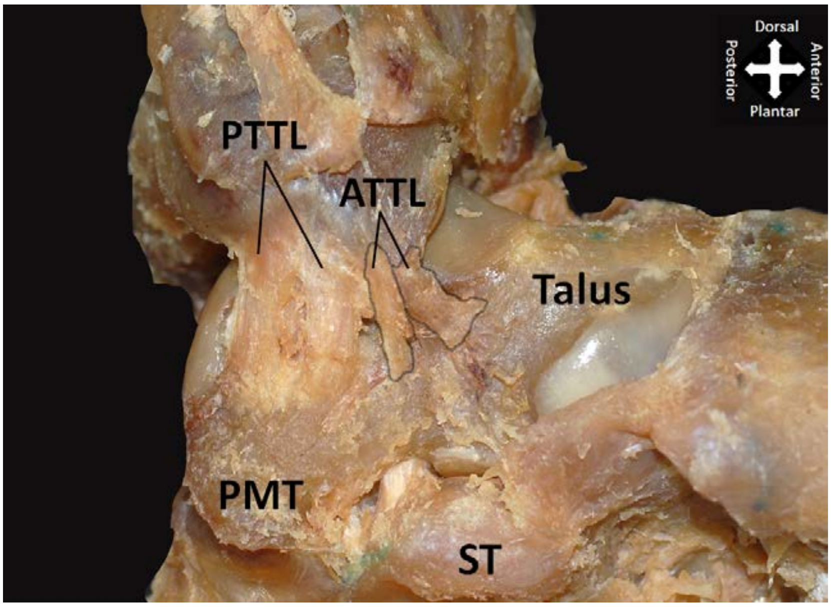

Figure 4.61 Two band form of the anterior tibiotalar ligament (ATTL): PTTL, posterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

4.12.2 Ligaments Superficial to the Anterior Tibiotalar Ligament (ATTL)

Ligaments superficial and covering the ATTL are shown in Table 4.36. The one band ATTL was deep to the TSL and TCL, TSL or TNL, TSL, TCL in 29.4%, 26.5% and 14.75% respectively: other ligaments covering it are shown in Table 4.36. The AATTL was deep to the TNL and TSL or the TNL or the TSL in 61.5%, 7.7% and 30.8% respectively. Ligaments that were superficial to the PATTL were the TNL and TSL (18.2%), TSL and TCL (63.6%), TSL (9.1%) and TCL (9.1%). There was no difference between males and females or between right and left sides in ligaments covering the ATTL.

Table 4.36 : Ligaments covering the anterior tibiotalar ligament (ATTL): AATTL, anterior band of the ATTL; PATTL, posterior band of the ATTL; TNL, tibionavicular ligament; TSL, tibiospring ligament; TCL, tibiocalcaneal ligament; PTTL, posterior tibiotalar ligament

ATTL deeper to	**Occurrence %**	**AATTL deeper to**	**Occurrence %**	**PATTL deeper to**	**Occurrence %**
TNL, TSL	11.80%	TNL, TSL	61.50%	TNL, TSL	18.20%
TNL, TSL, TCL	14.70%	TNL	7.70%	TSL, TCL	63.60%
TNL	2.90%	TSL	30.80%	TSL	9.10%
TSL, TCL	29.40%			TCL	9.10%
TSL	26.50%				
TCL	11.80%				
TNL, TSL, PTTL (partially)	2.90%				

4.12.3 Proximal Attachment of the Anterior Tibiotalar Ligament (ATTL)

The anterior tibiotalar ligament (ATTL) originated from the medial malleolus (Figures 4.54, 4.62). The one band ATTL was attached proximally to the medial surface and tip of the anterior colliculus, but in 21.1% of specimens it only attached to the medial surface and not the tip: other attachments are shown in

Table 4.37. The AATTL attached proximally to the anterior colliculus, being attached to its medial surface, medial surface and tip or anterior surface in 46.7%, 46.7% and 6.7% of specimens respectively (Table 4.37). The PATTL was mostly attached to the medial surface of the anterior colliculus (80%), but in 13.3% and 6.7% it inserted to the medial surface and tip or only the tip respectively (Table 4.37). No difference in the proximal attachment of the parts of the ATTL was observed between males and females or between right and left sides.

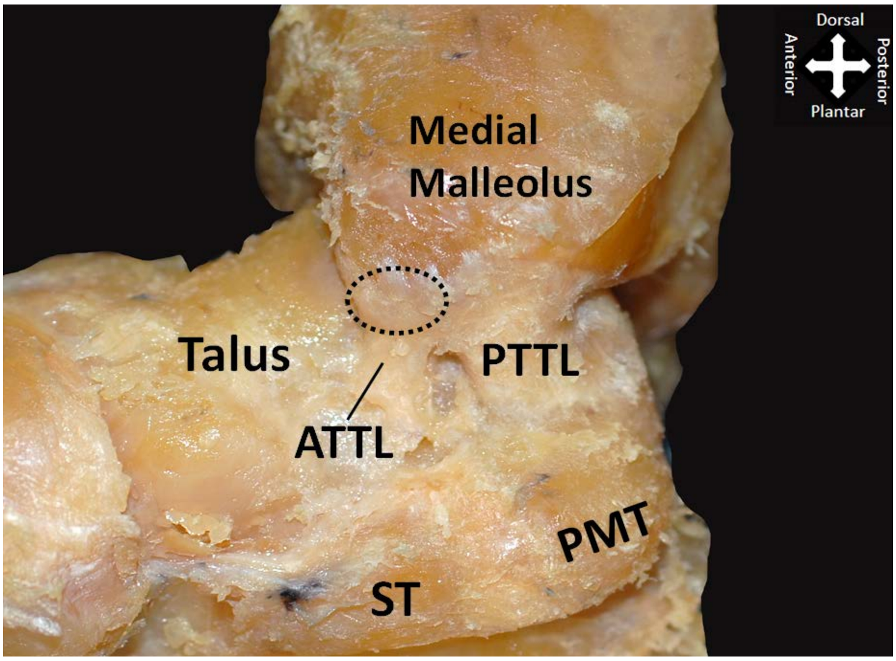

Figure 4.62 Proximal attachment (dotted circle) of the anterior tibiotalar ligament (ATTL): PTTL, posterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

Table 4.37 Proximal attachment of the anterior tibiotalar ligament (ATTL): AATTL, anterior band of the ATTL; PATTL, posterior band of the ATTL.

	Proximal Attachment	Occurrence %
ATTL	Anterior colliculus (medial surface)	21.10%
	Anterior colliculus (medial surface, tip)	71.10%
	Anterior colliculus (medial surface, tip, anterior surface)	2.60%
	Anterior colliculus (medial surface, tip, posterior surface)	2.60%
	Anterior colliculus (medial surface) and posterior to the tip	2.60%
AATTL	Anterior colliculus (medial surface)	46.70%
	Anterior colliculus (medial surface, tip)	46.70%
	Anterior colliculus (anterior surface)	6.70%
PATTL	Anterior colliculus (medial surface)	80%
	Anterior colliculus (medial surface, tip)	13.30%
	Anterior colliculus (tip)	6.70%

4.12.4 Distal Attachment of the Anterior Tibiotalar Ligament (ATTL)

The ATTL, AATTL and PATTL attached distally to the medial surface of the talus distal to the malleolar articular surface and anterosuperior to the posteromedial tubercle (Figure 4.63). The distance and angle between the distal attachment of the ATTL and posteromedial tubercle were 19.53 ± 3.71 mm and 27° ± 7° respectively. The AATTL distal attachment was 22.38 ± 2.96 mm anterosuperior to the posteromedial tubercle, forming an angle of 26° ± 9°. The PATTL was 16.56 ± 3.09 mm from the posteromedial tubercle with an angle of 24° ± 12°.

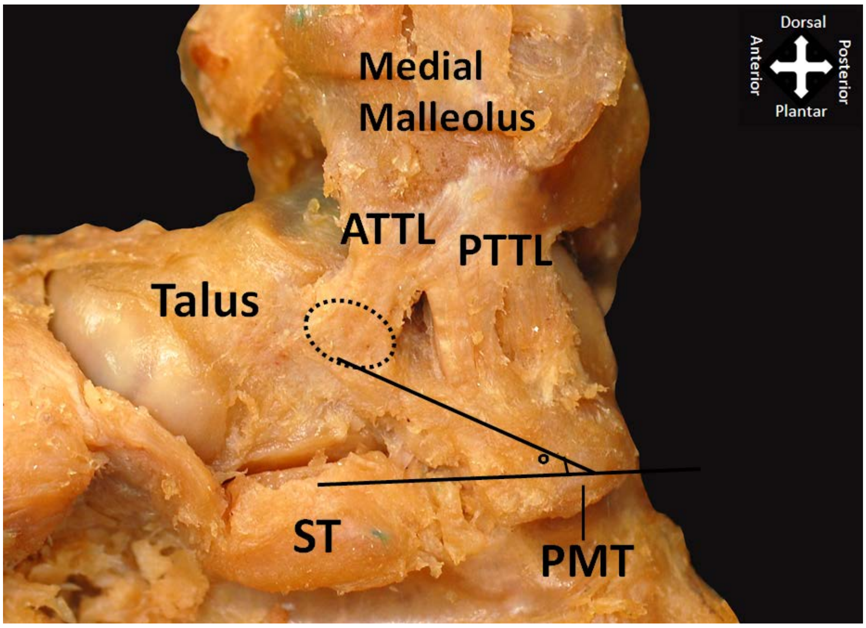

Figure 4.63 Distal attachment (dotted circle) of the anterior tibiotalar ligament (ATTL) showing the methodology of measuring the distance between the ATTL distal attachment and talar posteromedial tubercle (PMT): PTTL, posterior tibiotalar ligament; ST, sustentaculum tali.

There were no differences in the distances and angles between the distal attachments of the ATTL and the posteromedial tubercle between right and left sides or between males and females, except for the ATTL distal attachment distance to the posteromedial tubercle between genders ($P = 0.001$), being 21.95 ± 3.12 mm in males and 17.95 ± 3.21 mm in females. The ATTL distal attachment distance to the posteromedial tubercle was correlated with age ($r = -0.384$, $r^2 = 0.15$, $P = 0.017$), foot length ($r = 0.668$, $r^2 = 0.45$, $P < 0.001$) and 1st metatarsal length ($r = 0.505$, $r^2 = 0.26$, $P = 0.001$). The angle between the posteromedial tubercle and ATTL distal attachment was correlated with ligament length ($r = -0.397$, $r^2 = 0.16$, $P = 0.02$) only.

4.12.5 Anterior Tibiotalar Ligament (ATTL) Orientation

All fibres of the ATTL crossed laterally from the tibia to the talus (Figures 4.64, 4.65), with the ATTL oriented anteroinferiorly in neutral (83.3%), dorsiflexion (87.5%), plantarflexion (79.2%), inversion (79.2%) and eversion (89.5%). A posteroinferior orientation was seen in neutral, dorsiflexion, plantarflexion, inversion and eversion in 12.5%, 8.3%, 20.8%, 20.8% and 10.5% respectively, while an inferior orientation was observed in neutral (4.2%) and dorsiflexion (4.2%).

An anteroinferior orientation was observed for the AATTL in all joint positions. The PATTL always had a posteroinferior orientation in neutral, plantarflexion and inversion, while it was also seen in dorsiflexion and eversion in 66.7% and 50% respectively. In addition, the PATTL was orientated vertically inferior in dorsiflexion (33.3%) and eversion (50%).

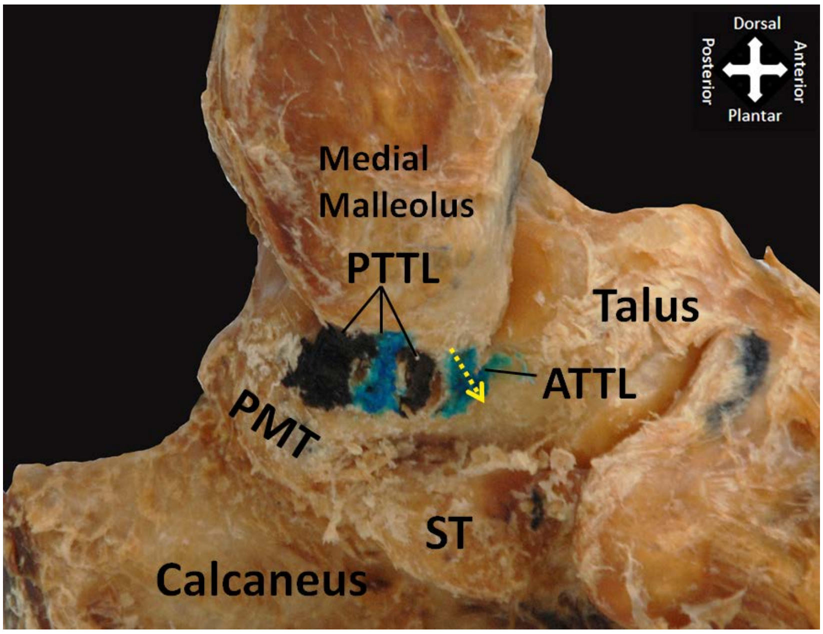

Figure 4.64 Anteroinferior orientation (yellow dotted arrow) of the anterior tibiotalar ligament (ATTL) in neutral position: PTTL, posterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

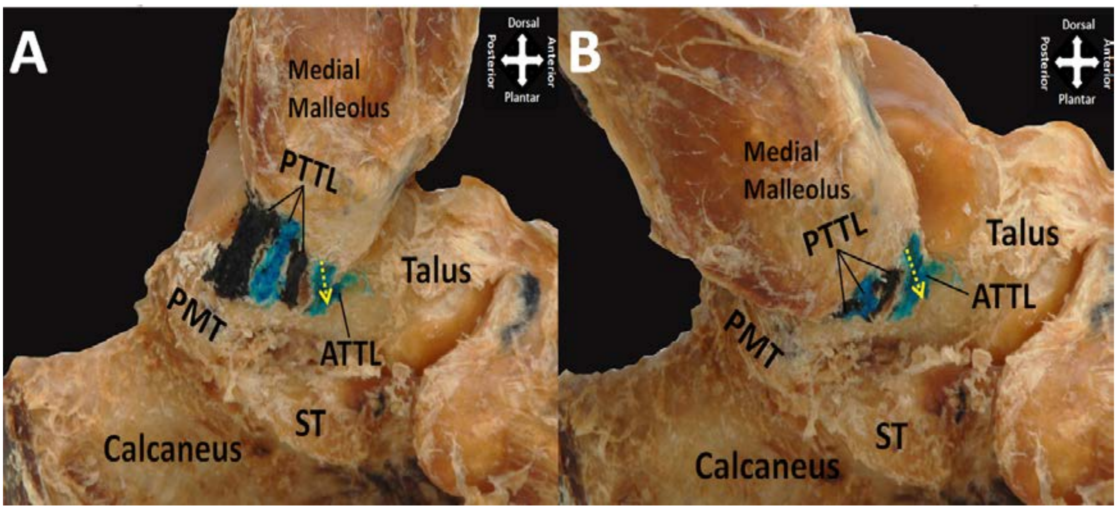

Figure 4.65 Orientation (dotted arrows) of the anterior tibiotalar ligament (ATTL) in dorsiflexion (A) and plantarflexion (B): PTTL, posterior tibiotalar ligament; ST, sustentaculum tali; PMT, posteromedial tubercle.

4.12.6 Anterior Tibiotalar Ligament (ATTL) Dimensions

Table 4.38 shows the dimensions of the different parts of the ATTL, which had a length, mid width and thickness of 10.15 ± 3.55 mm, 3.06 ± 1.51 mm and 0.76 ± 0.43 mm respectively. AATTL dimensions were 9.42 ± 2.93 mm (length), 2.84 ± 1.72 mm (mid width) and 0.59 ± 0.36 mm (thickness) (Table 4.38), while the PATTL had a length of 11.61 ± 3.27mm, mid width of 2.34 ± 1.1 mm and thickness of 0.68 ± 0.35 mm. No ATTL dimensions were different between right and left sides or between males and females, except for ATTL length which was significantly different between genders (P = 0.049), being 11.44 ± 3.98 mm in males and 9.11 ± 2.86 mm in females.

Table 4.38 Dimensions of the anterior tibiotalar ligament (ATTL): AATTL, anterior band of the ATTL; PATTL, posterior band of the ATTL.

		N	Mean ± SD (mm)
ATTL	**Length**	36	10.15 ± 3.55
	Proximal Width	40	3.61 ± 1.78
	Mid Width	38	3.06 ± 1.51
	Distal Width	40	4.83 ± 2.8
	Thickness	38	0.76 ± 0.43
AATTL	**Length**	14	9.42 ± 2.93
	Proximal Width	15	2.46 ± 0.8
	Mid Width	16	2.84 ± 1.72
	Distal Width	15	3.88 ± 1.84
	Thickness	14	0.59 ± 0.36
PATTL	**Length**	15	11.61 ± 3.27
	Proximal Width	16	2.17 ± 1.17
	Mid Width	16	2.34 ± 1.1
	Distal Width	16	3.42 ± 2.32
	Thickness	13	0.68 ± 0.35

Significant differences in the ATTL proximal ($P = 0.009$) and distal ($P < 0.001$) width compared to the mid width were observed: in addition, there was a significant difference between the ATTL distal and proximal widths ($P < 0.001$). AATTL distal width was significantly different to the proximal ($P = 0.001$) and mid ($P = 0.045$) width, with no difference between them suggesting that distal width is the widest. Furthermore, a significant difference in the PATTL proximal ($P = 0.014$) and mid ($P = 0.009$) width compared to distal width was observed, while there was no difference between the proximal and mid width.Significant correlations between the dimensions of the different parts of the anterior tibiotalar ligament and other parameters are shown in Table 4.39.

ATTL length was correlated with proximal width, mid width, distal width and thickness, and between ATTL proximal width and length, mid width, distal width and thickness. ATTL mid width was correlated with length, proximal width, distal width, thickness and NBA, and between ATTL distal width and length, proximal width, mid width and DBA. ATTL thickness was correlated with foot length, 1st metatarsal length, ligament length, proximal width and middle width.

Table 4.39 Significant correlations between the dimensions of the anterior tibiotalar ligament (ATTL) in the one band form and the anterior (AATTL) and posterior (PATTL) bands in the two band form and other parameters and factors.

Dimension	Correlation with	N	Correlation coefficient (r)	r^2	P Value
ATTL Length	Proximal Width	36	0.504	0.25	0.002
	Mid Width	36	0.486	0.24	0.003
	Distal Width	36	0.522	0.27	0.003
	Thickness	36	0.486	0.24	0.003
ATTL Proximal Width	Length	36	0.504	0.25	0.002
	Mid Width	38	0.831	0.69	< 0.001
	Distal Width	40	0.696	0.48	< 0.001
	Thickness	38	0.357	0.13	0.028
	PBA	31	0.401	0.16	0.025
ATTL Middle Width	Length	36	0.486	0.24	0.003
	Proximal Width	38	0.831	0.69	< 0.001
	Distal Width	38	0.769	0.59	< 0.001
	Thickness	38	0.459	0.21	0.004
	NBA	31	0.358	0.13	0.048
ATTL Distal Width	Length	36	0.522	0.27	0.003
	Proximal Width	40	0.696	0.48	< 0.001
	Mid Width	38	0.769	0.59	< 0.001
	DBA	31	0.571	0.33	0.001
ATTL Thickness	Foot Length	37	0.397	0.16	0.015
	1st Metatarsal Length	37	0.371	0.14	0.024
	Length	36	0.486	0.24	0.003
	Proximal Width	38	0.357	0.13	0.028
	Mid Width	38	0.459	0.21	0.004
AATTL Length	Distal Width	13	0.605	0.37	0.029
	PATTL Length	14	0.643	0.41	0.013
AATTL Proximal	Distal Width	14	0.729	0.53	0.003
AATTL Distal WiWidthdth	Length	13	0.605	0.37	0.029
	Proximal Width	14	0.729	0.53	0.003
	DBA	12	0.576	0.33	0.05
AATTL Thickness	Age	14	- 0.640	0.41	0.014
PATTL Length	Proximal Width	14	0.686	0.47	0.013
	AATTL Length	14	0.643	0.41	0.013
PATTL Proximal Width	Length	14	0.686	0.47	0.013
	Mid Width	15	0.854	0.73	< 0.001
	Distal Width	15	0.633	0.4	0.011
PATTL Middle Width	Proximal Width	15	0.854	0.73	< 0.001
	Distal Width	15	0.870	0.76	< 0.001
PATTL Distal Width	Proximal Width	15	0.633	0.4	0.011
	Mid Width	15	0.870	0.76	< 0.001

AATTL length was correlated with distal width and PATTL length, while proximal AATTL width was correlated with the distal width. Distal AATTL width was correlated with length and proximal width, while AATTL thickness was correlated with age. PATTL length was correlated with proximal width and AATTL length. There were also correlations between PATTL proximal width and length, the mid and distal widths. In addition, PATTL mid width was correlated with the proximal and distal width and between PATTL distal width and proximal and mid width.

4.12.7 Change in the Anterior Tibiotalar Ligament (ATTL) length

ATTL length in neutral (10.21 ± 3.58 mm) was significantly different from that in dorsiflexion (9.55 ± 3.47 mm; $P = 0.010$), plantarflexion (11.24 ± 3.83 mm; $P = 0.001$) and inversion (10.89 ± 3.5 mm; $P = 0.018$), but not in eversion (9.86 ± 3.65 mm) (Figure 4.66). In addition, a significant difference was found in length between dorsiflexion and plantarflexion ($P < 0.001$) and between inversion and eversion ($P < 0.001$). This suggests that the ATTL is taut in plantarflexion and inversion compared to neutral. The maximum applied dorsiflexed PROM was correlated with ATTL length in plantarflexion ($r = -0.353$, $r^2 = 0.12$, $P = 0.041$) and inversion ($r = -0.414$, $r^2 = 0.17$, $P = 0.015$). However, no other correlations between the change in ATTL length and the applied PROMs were observed.

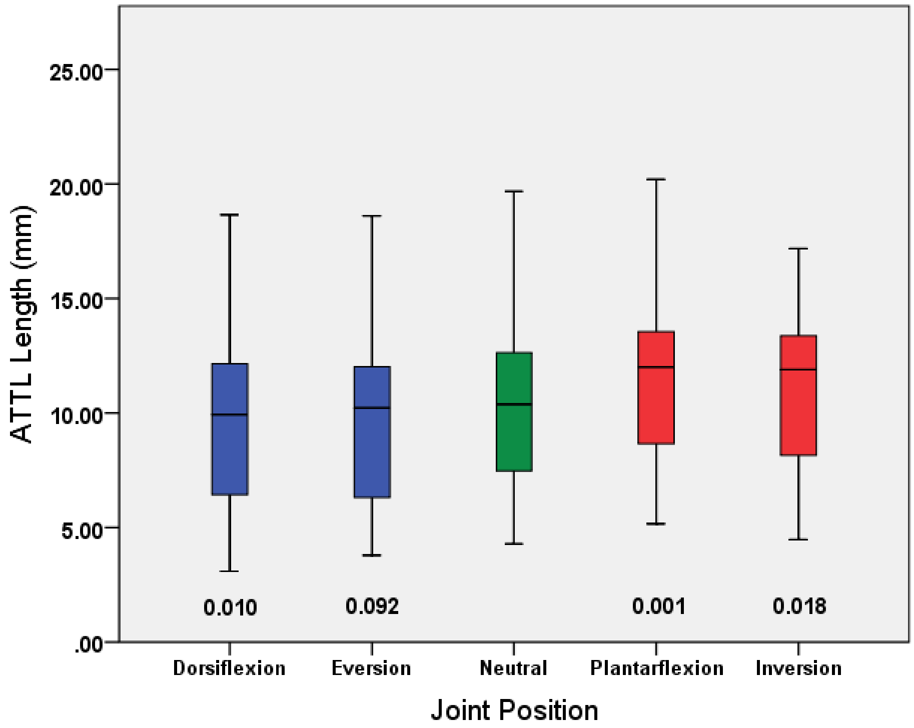

Figure 4.66 Change in the anterior tibiotalar ligament (ATTL) length in different joint positions.

In comparison to the AATTL length in neutral (9.42 ± 2.93 mm), there were significant differences in length in dorsiflexion (8.71 ± 3.22 mm; P = 0.012) and inversion (11.31 ± 3.76 mm; P = 0.004), but not in plantarflexion (10.96 ± 4.32 mm) and eversion (9.34 ± 3.51 mm). AATTL length in dorsiflexion was shorter than in neutral, while in inversion the ligament was longer and more taut than in neutral.

There was no difference in PATTL length in neutral (11.61 ± 3.27 mm) and dorsiflexion (11.37 ± 3.8 mm), plantarflexion (11.39 ± 3.25 mm), inversion (10.91 ± 3 mm) or eversion (11.60 ± 3.4 mm). No correlation was found in AATTL or PATTL length in different joint positions and all applied PROMs.

4.12.8 Anterior Tibiotalar Ligament (ATTL) Bony Attachment Lengths

The ATTL had a PBA, NBA and DBA of 21.37%, 57.34% and 21.29% of its total length in plantarflexion (Table 4.40). In addition, the AATTL had 61.15% of its length free, while 16.55% and 22.30% comprised the proximal (PBA) and distal (DBA) bony attachments. Furthermore, 63.04% of PATTL length was free from any bony attachments, with the proximal (PBA) and distal (DBA) bony attachment lengths being 16.69% and 20.27% respectively. There was no difference in ATTL, AATTL and PATTL bony attachment length between right and left sides or between males and females, except for ATTL NBA which showed a significant difference between genders (P = 0.045), being 7.63 ± 2.29 mm in males and 6.04 ± 1.93 mm in females.

Table 4.40 Bony attachment lengths of the anterior tibiotalar ligament (ATTL): AATTL, anterior band of the ATTL; PATTL, posterior band of the ATTL; PBA, proximal bony attachment length; NBA, no bony attachment length; DBA, distal bony attachment length.

		N	Mean ± SD (mm)	% of the total length (PF)
ATTL	**PBA**	31	2.52 ± 1.63	21.37%
	NBA	31	6.76 ± 2.21	57.34%
	DBA	31	2.51 ± 1.9	21.29%
AATTL	**PBA**	13	1.87 ± 0.9	16.55%
	NBA	12	6.91 ± 2.28	61.15%
	DBA	13	2.52 ± 1.7	22.30%
PATTL	**PBA**	12	2.01 ± 1.36	16.69%
	NBA	12	7.59 ± 2.22	63.04%
	DBA	12	2.44 ± 1.98	20.27%

ATTL PBA was correlated with the proximal width ($r = 0.401$, $r^2 = 0.16$, $P = 0.025$) and NBA ($r = 0.401$, $r^2 = 0.16$, $P = 0.025$), between ATTL NBA and mid width (r = 0.358, r^2 = 0.13, P = 0.048) and PBA (r = 0.401, r^2 = 0.16, P = 0.025). ATTL DBA was correlated with distal width (r = 0.571, r^2 = 0.33, P = 0.001).

There was a correlation between AATTL DBA and PATTL DBA (r = 0.804, r^2 = 0.65, P = 0.009) only. PATTL PBA was correlated with NBA (r = 0.710, r^2 = 0.5, P = 0.01), and PATTL NBA with PATTL PBA (r = 0.710, r^2 = 0.5, P = 0.01). In addition, there were correlations between PATTL DBA and thickness (r = 0.756, r^2 = 0.57, P = 0.007) and AATTL DBA (r = 0.804, r^2 = 0.65, P = 0.009).

4.12.9 Relation to Other Bands

The AATTL was not attached proximally to the PATTL in 11.11% of specimens, while in 88.89% it attached to the PATTL proximally separating 5.94 ± 2.72 mm distal to the proximal attachment of the AATTL: in half of these cases the AATTL extended 2.03 ± 0.99 mm proximally free without attaching to the PATTL. Distally, the AATTL was not attached to the PATTL in 25% of specimens, while in 75% it attached PATTL distally separating 1.82 ± 1.84 mm proximal to the distal attachment of the AATTL. In a small number of cases tiny fibre fasciculations from the ATTL were seen, but did not appear large enough to act as constricting independent bands.

4.13 Statistical Analysis Applied to the Lateral and Medial (Deltoid) Collateral Ligaments of the Ankle Joint

4.13.1 Differences in the Mid Width

Significant differences in the mid width of the LCL and MCL components are shown in Table 4.41. There were significant differences in mid width of ATFL total mid width, CFL, TNL, PTTL total mid width and ATTL compared to all LCL and MCL components. However, PTFL mid width was not different compared to that in TSL, TCL and STTL. In addition, there were no differences between the mid width of the TSL and that of PTFL and TCL, as well as no difference between the mid width of the TCL compared to the PTFL, TSL and STTL. STTL mid width was no different from that of the CFL and TSL.

This shows that the TNL was the widest and ATTL narrowest at the mid part of all LCL and MCL components. In the LCL components, the ATFL was the widest at its middle while CFL was the narrowest, being less wide than the PTFL at its middle. Among the MCL components, the TNL was widest followed by the PTTL which was significantly wider than the TSL, TCL and STTL: the ATTL was the narrowest at its middle.

Table 4.41 Significant differences in the middle width between the lateral (LCL) and medial (MCL) collateral ligaments of the ankle: ATFL, anterior talofibular ligament; CFL, calcaneofibular ligament; PTFL, posterior talofibular ligament; TNL, tibionavicular ligament; TSL, tibiospring ligament; TCL, STTL, superficial tibiotalar ligament; PTTL, posterior tibiotalar ligament; ATTL, anterior tibiotalar ligament.

Ligament	N	Middle Width (mm)	Difference compared to	P Value
ATFL Total Width	25	8.16 ± 1.75	CFL, PTFL, TSL, TNL, TCL, STTL, ATTL	< 0.001
			PTTL Total Width	0.010
CFL	25	3.56 ± 0.97	ATFL Total Width, PTFL, TSL, TNL, TCL, PTTL	< 0.001
			STTL	0.004
			ATTL	0.014
PTFL	25	5.63 ± 1.73	ATFL Total Width, CFL, TNL, PTTL Total Width, ATTL	< 0.001
TSL	25	5.61 ± 1.53	ATFL Total Width, CFL, TNL, PTTL Total Width, ATTL	< 0.001
			STTL	0.043
TNL	25	13.01 ± 3.51	ATFL Total Width, CFL, PTFL, TSL, TCL, STTL, PTTL Total Width, ATTL	< 0.001
TCL	25	5.38 ± 1.9	ATFL Total Width, TNL, PTTL Total Width, ATTL	< 0.001
STTL	25	4.75 ± 1.49	ATFL Total Width, TNL, PTTL Total Width, ATTL	< 0.001
			CFL	0.004
			TSL	0.043
PTTL Total Width	25	9.4 ± 2.05	CFL, PTFL, TSL, TNL, TCL, STTL, ATTL	< 0.001
			ATFL Total Width	0.010
ATTL	25	2.84 ± 1.28	ATFL Total Width, PTFL, TSL, TNL, TCL, STTL, PTTL Total Width, ATTL	< 0.001
			CFL	0.014

ATFL total mid width was correlated with the mid width of the CFL (- 0.307, r^2 = 0.09, P = 0.016), TCL (r = 0.318, r^2 = 0.1, P = 0.026), PTTL total mid width (r = 0.299, r^2 = 0.09, P = 0.037) and ATTL (r = 0.327, r^2 = 0.11, P = 0.048). In addition, there were correlations between the mid width of the PTFL and TCL mid width (r = 0.400, r^2 = 0.16, P = 0.005). The mid width of the TCL was correlated with the mid width of the ATFL, PTFL (r = 0.400, r^2 = 0.16, P = 0.005) and ATTL (r = 0.465, r^2 = 0.22, P = 0.005). Additionally, PTTL total mid width was correlated with the mid width of the ATFL and ATTL (r = 0.439, r^2 = 0.19, P = 0.007). CFL mid width was correlated with ATFL total mid width, while ATTL mid width was correlated with mid width of the ATFL, TCL and PTTL. However, the mid width of the TNL, TSL and STTL were not correlated with any LCL and MCL mid widths.

4.13.2 Differences in the Thickness

Significant differences in the thickness of the LCL and MCL components are shown in Table 4.42. The thickness of the CFL, PTFL and PTTL average thickness were significantly different compared to all other LCL and MCL components. ATFL average thickness was significantly different compared to all other LCL and MCL components except that of the TSL, TCL and STTL, while TSL thickness was not different to that of the ATFL, TCL, STTL and ATTL. In addition, there was no difference between TNL thickness and that of the TCL and ATTL; TCL thickness was not different compared to the thickness of the ATFL, TSL, TNL, STTL and ATTL. Furthermore, there were no differences between STTL thickness and that of the ATFL, TSL, TCL and ATTL, while the ATTL average thickness was not different compared to the thickness of the ATFL, TSL, TNL, TCL and STTL.

Table 4.42 shows that the PTFL was the thickest followed by the PTTL among all LCL and MCL components, while the TNL can be considered the thinnest. Among the LCL components, the PTFL was the thickestand the ATFL the thinnest, being significantly thinner than the CFL. Among all MCL components the PTTL was the thickest, while the TNL was the thinnest followed by the ATTL. In addition the STTL and TSL were significantly thicker than the TNL.

Table 4.42 Significant differences in the thickness between the lateral (LCL) and medial (MCL) collateral ligaments of the ankle: ATFL, anterior talofibular ligament; CFL, calcaneofibular ligament; PTFL, posterior talofibular ligament; TNL, tibionavicular ligament; TSL, tibiospring ligament; TCL, STTL, superficial tibiotalar ligament; PTTL, posterior tibiotalar ligament; ATTL, anterior tibiotalar ligament.

Ligament	N	Thickness (mm)	Difference compared to	P Value
ATFL[a]	27	0.75 ± 0.24	CFL, PTFL, PTTL[a]	< 0.001
			TNL	0.022
CFL	27	1.25 ± 0.41	ATFL[a], PTFL, TSL, TNL, STTL, ATTL[a]	< 0.001
			TCL	0.042
			PTTL[a]	0.049
PTFL	27	2.11 ± 0.62	ATFL[a], CFL, TSL, TNL, TCL, STTL, ATTL[a]	<0.001
			PTTL[a]	0.001
TSL	27	0.79 ± 0.35	CFL, PTFL, PTTL[a]	< 0.001
			TNL	0.013
TNL	27	0.61 ± 0.28	CFL, PTFL, PTTL[a]	< 0.001
			ATFL[a]	0.022
			TSL, STTL	0.013
TCL	27	0.88 ± 0.83	CFL	0.042
			PTFL	< 0.001
			PTTL[a]	0.002
STTL	27	0.78 ± 0.29	CFL, PTFL, PTTL[a]	< 0.001
			TNL	0.013
PTTL[a]	27	1.47 ± 0.54	ATFL[a], TSL, TNL, STTL, ATTL[a]	< 0.001
			CFL	0.049
			PTFL	0.001
			TCL	0.002
ATTL[a]	27	0.69 ± 0.45	CFL, PTFL, PTTL[a]	<0.001

[a]Average thickness of all bands

ATFL average thickness was correlated with CFL thickness ($r = 0.355$, $r^2 = 0.13$, $P = 0.013$), TNL ($r = 0.388$, $r^2 = 0.15$, $P = 0.012$) and ATTL average thickness ($r = 0.318$, $r^2 = 0.1$, $P = 0.026$). There were also correlations between CFL thickness and that of the ATFL, TSL ($r = 0.331$, $r^2 = 0.11$, $P = 0.034$), TNL ($r = 0.410$, $r^2 = 0.17$, $P = 0.010$) and ATTL average thickness ($r = 0.314$, $r^2 = 0.1$, $P = 0.033$). In addition, TSL thickness was correlated with CFL thickness, while TNL thickness was correlated with the thickness of the ATFL, CFL and ATTL ($r = 0.375$, $r^2 = 0.14$, $P = 0.013$).

TCL thickness was correlated only with PTTL thickness ($r = 0.447$, $r^2 = 0.20$, $P = 0.002$). There were also correlations between the PTTL average thickness and the thickness of TCL and ATTL ($r = 0.341$, $r^2 = 0.12$, $P = 0.015$). In addition, ATTL average thickness was correlated with ATFL, TNL and PTTL, while the thickness of the PTFL and STTL were not correlated with any parts of the LCL or MCL.

5 Discussion

5.1 Anatomy of the Anterior Talofibular Ligament (ATFL)

5.1.1 Band Number of the Anterior Talofibular Ligament (ATFL)

Inconsistency in the number of ATFL bands has been reported in the literature (Golano et al., 2010), with most studies observing the one or two bands (Rein et al., 2015; Clanton et al., 2014; Neuschwander et al., 2013; Yıldız and Yalcın, 2013; Raheem and O'Brien, 2011; Taser et al., 2006; Burks and Morgan, 1994; Wiersma and Griffioen, 1992). Other studies have observed one, two and three ATFL bands (Choo et al., 2014; Boonthathip et al., 2011; Uğurlu et al., 2010; Milner and Soames, 1997), some only one band (Wenny et al., 2014), two bands (Sindel et al., 1998), or two and three bands (Sarrafian, 1993): Raheem and O'Brien (2011) reported absence of the ATFL in 1 of 20 specimens examined.

In the current study, the ATFL consisted of one, two or three bands agreeing with Choo et al. (2014), Boonthathip et al. (2011), Uğurlu et al. (2010) and Milner and Soames (1997) and contradicting other investigations. This inconsistency may be due to the different dissection approaches used: in the current study care was taken during the dissection as some fibres were delicate and adherent to the joint capsule. Furthermore, some investigators may not have considered bands that bifurcated but were not completely separated or independent from each other proximally (Rein et al., 2015; Wiersma and Griffioen, 1992). The ATFL bands observed in the current study had different distal attachments but were joined proximally in all cases. An ATFL was observed in all specimens in the current study thus agreeing with all other studies, except Raheem and O'Brien (2011): this may have been due to a previous injury that destroyed the ligament.

These discrepancies in the reported number of the ATFL bands could be due to the variable ethnicities of the examined specimens in the previous investigations. For example, Clanton et al. (2014), Neuschwander et al. (2013) and Taser et al. (2006) are all investigations that were conducted in the United States, while others from were from different countries with different ethnic groups, such as Yıldız and Yalcın (2013) and Sindel et al. (1998) (Turkey), or Raheem and O'Brien (2011) (Ireland); in the current study the sample was taken from Scottish cadavers. However, future studies should investigate ankle collateral ligaments morphology among different ethnic groups. Also, individuals who lived during the early decades of the ninth century probably had a life style which was more active physically compared to today's sedentary life style; this may have affected the forces to which ankle ligaments were subjected, and therefore growth of the ligaments and their fasciculation into into multibanded ligaments. Moreover, the current study's findings are compared to various investigations that used different methodologies or different specimens; for example one factor that can be considered in explaining some of the variations in the morphology or the dimensions is nutrition; since many studies have no background information on the specimen used (which will be discussed in the following sections), it may be suggested that some specimens were taken from unclaimed bodies; these individulas may not have received sufficient nutrition, causing defiency and imbalance that may have affected the collagen content of the ligaments and and thus varaiable morphologies.

The results of the current study observed the one band form of the ATFL in 17.2% of specimens: compared to studies that reported the ATFL having one to three bands, this is similar to Uğurlu et al. (2010) who reported a 23% incidence. However, this disagrees with Choo et al. (2014) (9%), Boonthathip et al. (2011) (60%) and Milner and Soames (1997) (38%); Choo et al. (2014) investigated radiographic images of living voulnteers from korea with ages between 23 and 36 years old. The two band form of the ATFL was observed in more than half of the specimens (62.5%), being similar to Uğurlu et al. (2010) (59%) and Milner and Soames (1997) (50%), but contradicting Choo et al. (2014) and Boonthathip et al. (2011) who reported that the two band form was observed in 82% and 20% of specimens respectively. Choo et al. (2014) used 3D MRI to screen 33 ankles of living volunteers; MRI slice thickness may affect the visualisation of the ligament while dissection may lead to missing multibanded ATFLs. The inconsistency with Boonthathip et al. (2011) might be due to two causes; firstly, the small sample size of 10 frozen cadavers with mean age of 87.4 years and secondly using MRI in visualisation of the ATFL. The frequency of the three band form in the current study (20.3%) is similar to that of Boonthathip et al. (2011) (20%) and Uğurlu et al. (2010) (18%), but differs from Choo et al. (2014) (9%) and Milner and Soames (1997) (12%).The one, two and three band forms of the ATFL were found to be unilateral in 40%, 38.89% and 84.62% respectively and bilateral in 40%, 61.11% and 15.38% respectively. These findings differ from Milner and Soames (1997), who reported a unilateral occurrence in 20% (one band), 7.69% (two band) and 100% (three band) and a bilateral occurrence 80% (one band) and 92.31% (two band): the three band form was not observed bilaterally possibly due to their smaller number of specimens (n = 26) in relation to the present study; although the samples were taken from European Caucasian cadavers.

Sarrafian (1993a) reported the ATFL to consist mainly of two bands, with the superior band being the largest, and occasionally three bands. The ATFL splitting into different bands may allow small vessels to pass between them (Clanton et al., 2014; Sarrafian, 1993a): this was observed in the current study. In addition, Sarrafian (1993a) considered the IATFL as an accessory component, with the larger superior band being the main ATFL component. Choo et al. (2014) demonstrated, using MRI, that the single band ATFL was at the same location as the superior band in both the two or three band forms. The current study agrees with this concept of considering the superior ATFL band the main component, while the IATFL and MATFL bands are used to refer to the other bands in the two and three band forms.

In the current study, 70% of the two band form was observed in females, while 69.2% of the three band form was seen in male specimens Foot length and 1st metatarsal length represented foot size in the current study; however, neither had any association with the occurrence of the one and two band forms, but were associated with the presence of the three band form. Therefore, the three band form tends to be observed in specimens with longer feet (212.76 ± 24.34 mm) or 1st metatarsal length (67.10 ± 5.89 mm) suggesting that the extra length of the foot may require additional support from the ATFL in limiting talar motion within the ankle mortise, especially in extreme ROM. The two band form of the ATFL having no association with foot or 1st metatarsal length, as well as being the most commonly observed form (62.5%), suggests that it is the usual form of the ATFL, in which case the inferior band (IATFL) is not an accessory band as stated by others (Rein et al., 2015; Yıldız and Yalcın, 2013; Boonthathip et al., 2011 Raheem and O'Brien, 2011; Taser et al., 2006; Wiersma and Griffioen, 1992). However, some studies have reported the two band ATFL to be present in less than 1/3rd of specimens. The present findings are consistent with Uğurlu et al. (2010) and Milner and Soames (1997) who reported the majority (59%) and half (50%) of their specimens with two bands respectively. In addition, there were no differences between the number of ATFLs or the maximum PROM in dorsiflexion, plantarflexion, inversion and eversion; this suggests that bifurcating to different band forms has no effect on resisting different ankle movements.

In the current study, the one and two band forms of the ATFL were unilateral in about 40% of the specimens; however, the three band form was found to be unilateral, as it was seen in 84.62% of specimens; this again suggests that the three band form is uncommon as it has been seen bilaterally in 15.38% of specimens with three band form. In addition, the observation of all band forms of the ATFL were not different between the right and left sides; this suggests that the dominant side has no effect on the distribution of the different forms of the ATFL.

5.1.2 Proximal Attachment of the Anterior Talofibular Ligament (ATFL)

The commonly reported origin of the ATFL is to the anterior border of the lateral malleolus (Taser et al., 2006; Hua et al., 2008; Clanton et al., 2014): this was confirmed in the present study, as well as agreeing with Kumai et al. (2002) in attaching anterosuperiorly to the tip of the lateral malleolus. Connecting fibres between the CFL and IATFL, especially when there was an inferior band in the two and three band forms, was usually observed. One aim of the current study was to identify the exact proximal attachment of the ATFL; therefore, the tip of the lateral malleolus and the mid proximal attachment point of the ATFL were used as reference points between which the distances and angles were measured. Previous studies have reported the distance between the mid proximal attachment of the ATFL and the lateral malleolar tip between 10 mm and 13.32 mm (Taser et al., 2006; Sindel et al., 1998; Burks and Morgan 1994), which is in line with the current study (11 ± 3.04 mm). However, Wenny et al. (2014) reported the distance as 0.58 ±1.89 mm, much less than all other reports. Wenny et al. (2014) took their measurements from 17 formalin embalmed specimens, with no information on age or gender of the specimens and the methodology was also not given, so their reported findings are difficult to compare.Clanton et al. (2014) reported the distance for the single band form of the ATFL as 13.8 mm, while the distances between origin of the superior and inferior bands in the bifurcate form to the tip were 16.3 mm and 10.2 mm from the lateral malleolar tip. While Clanton et al. (2014) reported the distances for each band individually; in the current study the ATFL had a single wide proximal attachment in all band forms. As this proximal attachment was consistent this led to measurement from the mid attachment point to the lateral malleolar tip. Dimmick et al. (2008), in an MRI study that was carried out on living individuals from Australia, reported the distance between the proximal attachment and the lateral malleolar tip as 3 – 6 mm, significantly less than the current findings. Two ankles in their study had distances of 9 mm and 14 mm, Dimmick et al. (2008) described as being above the lateral malleolar tip suggesting that they could have measured the distance to the level above the malleolar tip and not to the attachment point itself: their methodology was far from clear.

Identifying the angle between the mid proximal attachment of the ATFL and the lateral malleolar tip may help in identifying the exact point of the ligament's proximal attachment. The current study found the ATFL mid proximal attachment to form an angle to the tip of the lateral malleolus of 61° ± 14°: this angle, which helps in determining the exact origin of the ATFL, has not been previously reported. In addition, a positive correlation between this angle and both foot length and 1st metatarsal length was observed, suggesting that larger or longer feet have larger angles between the ATFL proximal attachment and the lateral malleolar tip: this may help in understanding development of the ligament.

The angle between the ATFL and CFL, which was measured proximally, was 117° ± 14°, being consistent with other studies Uğurlu et al. (2010) (113°) and Yıldız and Yalcın (2013) (112° ± 14° on the right and 106° ± 19° on the left side). However, Raheem and O'Brien (2011) reported this angle in neutral, dorsiflexion and plantarflexion as 12°, 13° ± 6° and 13° ± 6° respectively; these results are markedly different from the present study; they reported that measurement of the angle was taken along half the distance (length) of both ligaments; however, their reported measurements of the angle are not comparable due to unclear methodology that was used. In addition, Yıldız and Yalcın (2013) disagree with the current finding as they reported differences between the right and left sides; additionally, their measurement was taken while the foot in the neutral position, while in the current study the angle was measured while the ankle in maximal plantarflexion. The angle between the

ATFL and CFL in the present study was consistent in relation to both foot and 1st metatarsal length, as well as the variability of the ATFL proximal attachment. The angle was significantly larger in the one band form (131°) compared to both the two (115°) and three (113°) band forms: this is most probably due to the wider proximal width of the ATFL in the two and three band forms compared to the one band form; the wider the ligament structure toward the CFL the smaller the angle that will be formed.Distal Attachment of the Anterior Talofibular Ligament (ATFL).

5.1.3 Distal Attachment of the Anterior Talofibular Ligament (ATFL)

In reviewing the literature there is disagreement concerning the distal attachment (insertion) of the ATFL, the disagreement mainly concerning to which part of the talus (body or neck) the ATFL inserts. In the current study all specimens had all ATFL bands inserting into the body of the talus, which is in agreement with Boonthathip et al. (2011) and Sarrafian (1993a), but disagrees with Palastanga et al. (2006), Sindel et al. (1998), Milner and Soames (1997) and Wiersma and Griffioen (1992) who all reported it attaching to the neck of the talus. This difference may be attributed to the dissection technique used, as well as how much dissection was done to reveal the distal attachment of the ligament - this is not clear in the published illustrations in these studies; it could be argued that their findings are not accurate due to unclear methodologies that were illustrated, as well as failing to provide clear photographic evidence of the distal attachment to the talar neck. However, others have defined the ATFL distal attachment as being at the junction between the body and neck of the talus (Neuschwander et al., 2013) or into the facet lateral to the neck and the anterior aspect of the lateral articular surface of the talus (Hua et al., 2008: Kumai et al., 2002). No attachment to the calcaneus was observed in the current study; Uğurlu et al. (2010) reported one case of an inferior band in a three band form attaching distally to the calcaneus, however this is not significant.

The exact distal attachment in the current study was identified in relation to a consistent part of the talus, the talar anterolateral malleolar line (ALML). This reference line has not been used previously even though it is consistent, easy to define and in close proximity to the distal attachment of the ATFL bands. All ATFL bands in all forms inserted into the body of the talus anteromedial to the ALML, with the distance between the ATFL and the ALML being 4.46 ± 1.51 mm. In addition, the distance between the main ATFL band and the subtalar joint was also measured to give an accurate identification of the ATFL distal attachment. The ATFL inserted 18.74 ± 2.73 mm superior to the subtalar joint, being similar to Sindel et al. (1998) and Burks and Morgan (1994) who reported this distance as 14.2 ± 1.78 mm and 18 mm respectively.

In the current study, the IATFL mid attachment distance to the ALML was 4.27 ± 2.03 mm and to subtalar joint 11.13 ± 2.02 mm, being similar and shorter than that of the ATFL respectively. That the distance to the ALML was not affected could be due to the horizontal orientation of the both bands in relation to the ALML, while the distance to the subtalar joint was shorter because of the inferior location of the band in relation to the ATFL. The mid distal attachment of the IATFL to the ALML is influenced by a number of factors including gender, number of bands, and both foot and 1st metatarsal length. The distance in males (5.14 mm) was significantly longer than that in females (3.67 mm), probably due to significantly longer foot length in males (215.9 ± 18.7 mm) compared to females (190.1 ± 8 mm). This is supported by the positive correlation between this distance and foot length and 1st metatarsal length, in which males had longer lengths; however, there was no difference in the distance to the subtalar joint. The IATFL distal attachment distance to the ALML was significantly longer in the three band form (5.45 mm) compared to the two band form (3.88 mm) of the ATFL. Furthermore, the distance between the IATFL distal attachment and the subtalar joint was longer in the two band form (11.85 mm) compared to the three band form (8.00 mm) of the ATFL: this can be explained by the more inferior location of the IATFL in the three band form. These observations support the claim that the two band form of the ATFL is the most common form. The reported mid distal attachment of the MATFL distance to the ALML and subtalar joint were similar (4.11 ± 1.19 mm) and longer (14.27 ± 2.03 mm) than those of the IATFL respectively: this is probably due to the superior location of the band in relation to the IATFL.

The present study determined the distances between the mid distal attachment of the ATFL and the ALML and the subtalar joint as this helps in identifying the exact distal attachment of the ATFL by measuring both the vertical and horizontal distances to obtain the midpoint of the attachment on the talus. Therefore the point of distal attachment should be easily located and not confused with respect to the vertical or horizontal lines of the talar attachment. However, there are other referencing points to locate the distal attachment, including the distance between the ATFL distal attachment and the superior and inferior surfaces of the body of the talus (Taser et al., 2006). This is similar to the vertical measurement of the distance between the ATFL distal attachment and the subtalar joint. Clanton et al. (2014) located the distal insertion of the ATFL by measuring the oblique distances between the ATFL distal attachment and the anterolateral corner of the trochlea superiorly and the lateral talar process inferiorly; these two oblique lines help to locate the exact attachment. However, the two reference points (lateral talar process and the anterolateral corner of the trochlea) do not provide as good an approximation of the ATFL insertion as the two reference points used in the present study (ALML and subtalar joint line vertically). Furthermore, dissection or removal of structures might be required to reach to the anterolateral corner of the trochlea as it is located superior to the talar articular surface anterior to the ankle joint. This might not be the best reference point to use in surgical repair compared to the anterolateral malleolar line (ALML).

5.1.4 Anterior Talofibular Ligament (ATFL) Dimensions

ATFL length measured in the present study (19.58 ± 3.47 mm) compared to the length reported in previous studies is shown in Table 5.1. The current finding is in line with the majority of previous studies; however there are some disagreements. One possible explanation for these differing results is the methodology usd in measuring ATFL length. For example, Milner and Soames (1998a) measured the ATFL free length from its proximal to distal insertions, which could account for their shorter length. Similarly, Wenny et al. (2014) stated that the measurements reported were not for the longest fibres, but to the insertion points taken with the ligament under slight tension. In addition, they reported different lengths of the ATFL; proximal/posterior (12.85 ± 2.64 mm) and plantar/anterior (11.38 ± 2.25 mm) lengths; however, the methodology of measuring these lengths was not explained.

Table 5.1 ATFL length reported in previous studies compared to the current study[a].

Study	**N**	**Length (mm)**	**Study**	**N**	**Length (mm)**
Ruth, 1961	45	12	Siegler et al., 1988	20	17.81 ± 3.05
Buzzi et al., 1993	10	17.5	Sarrafian, 1993a	NK	15
Burks and Morgan, 1994	39	24.8	Luo et al., 1997	11	11.5 ± 2.5
Milner and Soames, 1998a	40	13 ± 3.9	Sindel et al., 1998	24	19.1 ± 2.28
Ozeki et al., 2002	12	19.8 ± 1.92	Mkandawire et al., 2005	5	18.89 ± 2.97
Taser et al., 2006	42	22.37 ± 2.5	De Asla et al., 2009	4	16.3 ± 3
Uğurlu et al., 2010	22	14.38 - 20.84	Boonthathip et al., 2011	10	21.2 ± 5.6 (MRI)
Raheem and O'Brien, 2011	20	15.5 ± 7.7	Neuschwander et al., 2013	8	19.7 ± 1.2
McDermott et al., 2004	20	19 ± 9.4, 15 ± 2.85 (MRI)	Wenny et al., 2014	17	12.85 ± 2.64, 11.38 ± 2.25
Haytmanek et al., 2015	11	9.4 ± 2.4 (lateral), 12.6 ± 1.8 (mortise)	**Current study**	**59**	**19.58 ± 3.47**

[a] all studies measured the length directly except De Asla et al. (2009) (MRI) and Haytmanek et al. (2015) (radiography: miniature fluoroscopy)

Ruth (1961), Uğurlu et al. (2010), Raheem and O'Brien (2011), Sarrafian (1993a) and Luo et al. (1997) all reported shorter ATFL lengths compared to the current study: they may have measured the free ligament length without involving the proximal and distal bony attachments. In further support of this most studies did not give detailed information on the methodology used in measuring ATFL fibre length. Haytmanek et al. (2015) reported shorter ATFL lengths (9.4 ± 2.4 mm in lateral view: 12.6 ± 1.8 mm in mortise view) using radiography (miniature fluoroscopy): this difference may be due to measuring the distance between the ATFL proximal and distal attachments only and the inability of radiography to show all the fibres of the ligament, especially those attached proximally to the fibula or distally to the talus. This is supported by McDermott et al. (2004) who found ATFL length to be shorter in MRI measurement (15 ± 2.85 mm) compared to direct physical measurement (19 ± 9.4 mm). Therefore, it could be argued that MRI measurements can be accepted for clinical applications but not to represent the actual physical length that can be measured either through dissecting cadavers or operating on patients. Most studies which reported multiband ATFLs did not state whether the reported length was the average length of all bands or the length of the main band. Moreover, the ankle joint position will influence ATFL length and the distance between the anterior border of the fibula and talar ATFL distal attachment, which may cause the ligament to be significantly elongated or shortened, especially if the methodology for measuring ATFL length was not explained.

The lATFL in the current study was 15.89 ± 3.11 mm, being consistent with Sindel et al. (1998) (15.2 ± 2.62 mm), Neuschwander et al. (2013) (16.7 ± 1.1 mm) and Uğurlu et al., (2010), who reported lATFL length as 15.33 mm and 16.12 mm in the two and three band forms respectively (Uğurlu et al., 2010). Burks and Morgan (1994) reported lATFL length (21 mm) longer than the current study: these same authors also disagree with the current study's observation of longer ATFL length. MATFL length (16.78 ± 4.41 mm) was similar to that of Uğurlu et al. (2010) (14.46 mm), which is the only study to that report this band length.

In reviewing the literature (Table 5.2) it is not clear whether the widths reported are the total width of the ATFL or the width of the main band. There are two exceptions: Sindel et al. (1998) and Burks and Morgan (1994) reported the width of the ATFL main band as 6.7 ± 1.06 mm and 7.2 mm respectively, which is considerably wider than in the present study (4.72 ± 1.41 mm). There is no specific explanation for this, but as Burks and Morgan (1994) reported observing only the one and two band forms and Sindel et al. (1998) only the two band form this may be why wider ligaments were reported. It is also possible that insufficient dissection was undertaken to reveal a third band, resulting in measuring the superior and middle bands together. In addition, Sindel et al. (1998) did not record the gender or feet side that were investigated. Thecurrent study observation of middle total width is in accordance with those reported by Sarrafian (1993a), Burks and Morgan (1994), Taser et al. (2006), Uğurlu et al. (2010) and Raheem and O'Brien (2011); however it disagrees with Ruth (1961), Buzzi et al. (1993), Milner and Soames (1998a), Boonthathip et al. (2011) and Yıldız and Yalcın (2013). One possible explanation could be that most studies that measured ATFL width did not specify if it was measured at the proximal, middle or distal parts of the ligament. Furthermore, Ruth (1961), Buzzi et al. (1993) and Milner and Soames (1998a) did not explain the methodology of measuring ATFL width; additionally, Ruth (1961) measured the length in dissected specimens, as well as from operations that was done to treat ankle sprain. In contrast, Yıldız and Yalcın (2013) indicated that the width measurement of the ATFL was taken at the mid length of the ligament, although their results still differ from the current study, being greater; additionally, this may be caused by the fact that all specimens that were used by Yıldız and Yalcın (2013) were taken from male cadavers.

Wendy et al. (2014) reported different widths of the ATFL; talar/ calcaneal (6.62 ± 1.39 mm) and fibular/tibial (6.5 ± 1.51 mm); however, the methodology of measuring these widths were not explained, making it hard to draw comparisons. ATFL width reported by Boonthathip et al. (2011) was measured from MRI and taken at the point where the ligament was widest; however, the width reported was small compared to the current study and can probably be explained by the variability of MRI visualisation and slice thickness used.

Table 5.2 ATFL width reported in previous investigations compared to the current study[a].

Study	N	Width (mm)	Study	N	Width (mm)
Ruth, 1961	45	5	Buzzi et al., 1993	10	10.8
Sarrafian, 1993a	NK	8	Burks and Morgan, 1994	39	7.2
Milner and Soames, 1998a	40	11 ± 3.3	Sindel et al., 1998	24	6.7 ± 1.06
Taser et al., 2006	42	6.75 ± 2.89	Uğurlu et al., 2010	22	7.61 - 12.98
Boonthathip et al., 2011	10	4.4 ± 1 (MRI)	Raheem and O'Brien, 2011	20	10 ± 7
Yıldız and Yalcın, 2013	46	11.07 ± 5.63	**Current Study**	**62**	**4.72 ± 1.41 (main band), 8.03 ± 1.92 (total width)**

[a] all studies measured the width directly except Boonthathip et al., 2011 (MRI)

In the current study ATFL width was measured at the proximal, middle and distal parts of the ligaments, as well as being measured for each individual band: the proximal and distal total ATFL widths were 8.14 ± 3.24 mm and 7.22 ± 2.02 mm respectively. These are close to those of Taser et al. (2006), who reported the width as 10.77 ± 1.56 mm (proximal) and 10.96 ± 2.38 mm (distal), as well as those reported by Buzzi et al. (1993) who reported the proximal and distal widths being 10 mm. The distal total width of the ATFL was significantly wider in males (8.24 mm) compared to females (6.52 mm): probably due to foot size in males being larger as discussed earlier.

IATFL width reported previously range between 2.1 mm and 4.92 mm (Choo et al., 2014; Yıldız and Yalcın, 2013; Uğurlu et al., 2010; Sindel et al., 1998; Burks and Morgan, 1994) and is consistent with the observations of the present study (3.63 ± 1.29 mm). In the present study, IATFL middle width in the two and three band form was 3.78 ± 1.25 mm and 3.14 ± 1.35 mm, which are both greater than those reported by Choo et al. (2014) (2.5 mm and 2.1 mm respectively). However their measurements were taken from 3D MRI scans which may have affect the measurement, as well as small sample size used to measure the middle width of the IATFL in the two and three band forms (27 and 3 respectively). In the current study the sample size was 37 and 12 respectively. Uğurlu et al. (2010) reported the MATFL as 4.44 mm wide, which is greater than in the current study (2.3 ± 0.71 mm): this may be explained by the smaller number of specimens (4) with three band form found by Uğurlu et al. (2010) compared to 12 specimens in the current study; measurements may not be accepted due to the sample size. However, Choo et al. (2014) reported MATFL width (2.1 mm) in three specimens which is closer to that observed in the present study.

In the present study, the single band of the ATFL had a middle width of 6.02 ± 1.64 mm, being significantly greater than the superior band in the two (4.65 ± 1.12 mm) and three (3.91 ± 1.41 mm) band forms. This is in agreement with Choo et al. (2014) who reported the middle width of the ATFL single band, superior band of two and three band forms as 5.5 mm, 5.1 mm and 3 mm respectively.

In the current study, the two and three band forms of the ATFL were significantly wider proximally (9.24 ± 1.89 mm and 9.81 ± 2.32 mm), at their middle (8.24 ± 1.71 mm and 8.94 ± 1.76 mm) and distally (7.27 ± 1.69 and 8.74 ± 1.56 mm) compared to the one band form which had proximal, middle and distal widths of 5.1 ± 2.22 mm, 6.02 ± 1.64 mm and 5.02 ± 1.89 mm respectively. These observations are in agreement with Uğurlu et al. (2010) who reported the widths of all bands in the two (10.31 mm) and three (12.98 mm) band forms being wider than those found in the single band form (7.61 mm), suggesting that ATFL width is influenced by the number of bands leading to a wider area of support in the two and three band forms compared to the one band form.

In the current study ATFL width was similar on the right and left sides, differing from Yıldız and Yalcın (2013) who reported single ATFL and the IATFL in the two band form being wider in right feet compared to left feet: the superior band of the ATFL in the two band form was wider on the left compared to the right. In the present study the main ATFL length was positively correlated with its mid width and thickness, suggesting that a longer ligament may need to be wider and thicker to provide sufficient support, to function. In addition, longer feet were observed to have wider total proximal and distal widths as there was a positive correlation between them, suggesting the need for wider proximal and distal attachments of the ligament in larger feet; however, the total mid width was positively correlated with 1st metatarsal length but not foot length.

Sarrafian (1993a) reported ATFL thickness as 2 mm: no dissection based studies have measured the ATFL thickness; the current study is the first to report the thickness at the midlength, adding morphological details that were missing in all dissection based studies. Knowing ATFL thickness may help in understanding the mechanical properties of the ligament, as well as in selecting the most appropriate graft for reconstruction. A number of studies have measured ATFL thickness from MRI images and reported thicknesses between 1.46 mm and 2.44 mm (Hua et al., 2008; Dimmick et al., 2008; Butler and Walsh, 2004; Ahmad et al., 1998). It is not surprising that these findings differ from those in the current study, which directly measured thickness using digital callipers giving thicknesses of 0.94 ± 0.35 mm for the ATFL, 0.57 ± 0.25 mm for the IATFL and 0.61 ± 0.29 for the MATFL. Choo et al. (2014) also reported the thickness of the different ATFL bands from 3D MRI scans, with the thickness of the single band, superior band in the two and three band forms being 2.3 mm, 1.9 mm and 1.4 mm respectively, significantly greater than that found in the current study (0.73 ± 0.34 mm, 1.02 ± 0.34 mm and 0.84 ± 0.32 mm). They also reported the thickness of IATFL in the two band and three band forms as 1.0 and 1.4 mm respectively, again being greater than the current observations (0.55 ± 0.22 mm and 0.63 ± 0.34 mm): Choo et al. (2014) also reported the thickness of the MATFL (1.5 mm), again significantly thicker than in the present study. These differences in the reported thickness may be due to the measurements using MRI from living individuals; additionally MRI slice thickness and the software that is used to measure the thickness are possible factors in producing these differences.

5.1.5 Anterior Talofibular Ligament (ATFL) Bony Attachment Lengths

As part of understanding the morphology and function of the ATFL, the bony attachment lengths, and the free length of the ligament should be determined. Most previous studies did not consider the proximal or distal bony attachment lengths of the LCL components. Burks and Morgan (1994) and Sindel et al. (1998) reported the proximal bony attachment length (PBA), i.e. the proximal/distal dimension of the ATFL fibular attachment, as 8.2 mm and 7.5 ± 1.32 mm respectively, similar to the current study (5.08 ± 3.31 mm). The distal bony attachment length (DBA), i.e. the ATFL proximal/distal talar attachment, has been reported as 8.7 mm (Burks and Morgan, 1994) and 6 ± 0.99 mm (Sindel et al., 1998): these results disagree with the current study (3.1 ± 1.98 mm). These conflicting observations may be due to the different dissection techniques used to reveal the exact proximal and distal attachments and the removal all the other structures and tissues that may blend with or be connected to these attachments as it was done in the present study; these reported results seem to be much larger, but a clear definition for the most proximal attachment was not provided.

The no bony attachment (free) length (NBA) in the current study was 12.22 ± 3.57 mm, which comprised 59.90% of the total length, while the PBA and DBA comprised 24.9% and 15.20% respectively. The reported free length by Milner and Soames (1998a) of 13 ± 3.9 mm is similar to the current study. However, no previous studies have reported the bony attachment lengths of the IATFL or MATFL bands of the ATFL. The IATFL had a PBA, NBA and DBA comprising 22.26%, 58.50% and 18.92% of the total length respectively, while the MATFL in the three band form had a PBA, NBA and DBA comprising 22.74%, 64.19% and 13.06% of the total length respectively. Knowing the free length of a ligament (no bony attachment length; NBA) may help in understanding the flexibility and strain behaviour of a ligament; additionally, it may give information on the required free length that enables the ligament to support joints and restricting movement without limitation in the normal range of motion.

The ATFL DBA was positively correlated with the total distal width, suggesting that an ATFL with a longer DBA has a wider total distal width; while total middle width was positively correlated with the IATFL NBA. Although most studies did not measure bony attachment lengths, Clanton et al. (2014) reported the fibular attachment area of the ATFL, while three other investigations reported the talar attachment footprint area (Clanton et al., 2014; Wenny et al., 2014; Neuschwander et al., 2013). Knowing the footprint area of the proximal and distal attachment areas is helpful in understanding the attachment behaviour of the ligaments, as well as their functional characteristics. However, defining the proximal and distal areas of attachment is not as easy or practical as measuring the bony attachment lengths (PBA and DBA), as well as the distal width, especially in surgical reconstruction procedures. In addition, the distal attachment area of the superior band of the ATFL was reported to be 47 mm^2 (Clanton et al., 2014) and 150 ± 26.00 mm^2 (Neuschwander et al., 2013); while the inferior band had a talar attachment area of 42 mm^2 (Clanton et al., 2014) and 90.0 ± 7.00 mm² (Neuschwander et al., 2013); this showed inconstancy in the reported area of the distal attachment of the ATFL. Both studied used fresh frozen specimens; however, Clanton et al. (2014) measured the area of the distal footprint mathematically using Heron's formula used to measure the areas, while Neuschwander et al. (2013) used ankle CT scans of the footprint surface that were analysed using computer software to calculate the distal footprint area.

5.1.6 Relations

The current study provided information on the relationships between the different bands of the ATFL as well as other surrounding ligaments. One of the important observations was that the ATFL and CFL had connecting fibres at their proximal origin: it was often difficult to separate their attachments completely, although in some cases when they were not connected other tissues and the periosteum seemed to maintain this connection at their origin. These detailed relationships help in describing the morphology of the multiband ATFL, as well as their relations and connections to the CFL and LTCL, which has not been previously reported. In addition, a deep band of the ATFL observed in the present study has not been previously documented; it was independent and deep to the ATFL. It is possible that this double layering of bands may have occurred as a result of ATFL division during growth.

5.2 Anatomy of the Calcaneofibular Ligament (CFL)

5.2.1 Proximal Attachment of the Calcaneofibular Ligament (CFL)

The CFL proximal attachment has been variably reported in the literature: in the current study it attached proximally to the anterior border of the inferior aspect of the lateral malleolus, thus agreeing with Kitsoulis et al. (2011), and inferior to the origin of the ATFL. In relation to the tip of the lateral malleolus, the CFL originated anterior to the tip, extending to the tip and medial to the tip in 82.1%, 16.1% and 1.8% of specimens respectively. Previous studies have reported contradictory proximal attachments with respect to the lateral malleolar tip. The current study disagrees with Sarrafian (1993a) and Wiersma and Griffioen (1992), who both demonstrated that the proximal attachment did not extend to the lateral malleolar tip. It also contradicts reports that indicate that the CFL always originates below the tip (Hua et al., 2008). These contradictory findings might be explained by the methodology used, i.e. how much dissection was carried out and how the ligament fibres were preserved as well as the nature of the specimens. For instance, Wiersma and Griffioen (1992) did not demonstrate the type of the embalming that was used in the examined specimens; while Hua et al. (2008) used MRI to investigate CFL on fresh ankles from ambuted legs; therefore, those findings can not be compared to the findings of the current study.

Defining the exact site of the CFL proximal bony attachment may aid surgical reconstruction, as well as help in understanding the function and behaviour of the ligament during ankle movements involving the fibula. The exact site of the CFL proximal attachment was defined in the current study in a similar way to that of the ATFL by measuring the distance and angle between the mid proximal attachment and the lateral malleolar tip. The CFL proximal attachment was 7.63 ± 3.47 mm from the lateral malleolar tip, being in the range reported by Sindel et al. (1998) and Clanton et al. (2014) (7.3 ± 1.49 mm and 5.3 mm, respectively). Burks and Morgan (1994) measured the length of a vertical line from the proximal attachment to the level of the tip and not the actual oblique line to the tip: their distance was 8.5 mm. The angle between the CFL proximal attachment and the lateral malleolar tip was not reported in previous studies: in the current study it was 55° ± 21°. Choosing the tip of the lateral malleolus as the reference point from which both the distance and angle of the CFL proximal attachment is measured provides a practical and efficient method of locating its origin due to the accessibility of locating the tip, as well as the close proximity of the tip to the origin.

5.2.2 Distal Attachment of the Calcaneofibular Ligament (CFL)

There is agreement regarding the CFL insertion to the lateral surface of the calcaneus; however it has been reported that it is not possible to exactly locate the CFL distal attachment because of the way the CFL inserts into the calcaneus (Yıldız and Yalcın, 2013). Furthermore, Burks and Morgan (1994) state that surgeons reconstructing the CFL may not recognise the exact site of its distal attachment. Contrary to these reports it is possible to locate the exact distal attachment of the CFL despite its variability in size, shape, direction (orientation) and behaviour in spreading out distally on the calcaneus. Previous studies have concluded that the CFL is always distally attached to the lateral calcaneal surface, being posterosuperior to the fibular tubercle (Clanton et al., 2014; Palastanga et al., 2006; Taser et al., 2006; Sarrafian, 1993). These reports partly agree with the current study, which found that 81.4% of specimens had an attachment posterosuperior to the fibular tubercle, with a posteroinferior location in 18.6% of specimens. These differences may be due to the small sample size (n=14) of Clanton et al. (2014) or due to some distal fibres of the CFL insertion being lost during dissection; additionally, Clanton et al. (2014) examined a younger age group (50.4 years) and feet with mean length 252 mm, compared to the current study (83.54 years and 200.9 mm respectively). In addition, differences in CFL length in relation to its posterosuperior (29.53 mm) and posteroinferior (34.21 mm) attachment to the fibular tubercle was found in the current study, giving further support to the possibility of losing some distal CFL fibres during dissection, thus resulting in a shorter ligament with a distal attachment posterosuperior to the fibular tubercle.

One of the aims of the current study was to locate the precise distal attachment of the CFL; the fibular (peroneal) tubercle was therefore used as the reference point to which the distance and angle from the CFL the mid distal attachment was determined. The distance between the fibular tubercle and distal attachment of the CFL was 17.7 ± 4.48 mm, being slightly greater than that reported by Clanton et al. (2014) (16.3 mm) and Buzzi et al. (1993) (13.2 mm), but significantly less than reported by Neuschwander et al. (2013) (27.1 ± 1.0 mm). These differences are probably due to the points from which the measurement was taken: Clanton et al. (2014) and Buzzi et al. (1993) measured the distance from the CFL distal footprint and not as done in the present study, while Neuschwander et al. (2013) measured the distance from a point slightly superior to the distal attachment than used in the present study. In addition, they had a smaller sample size (n = 8). Measuring the angle between the distal CFL attachment and the fibular tubercle may help in better localisation of the distal insertion point of the ligament. The current study is the first to provide this angle adding further information than just the distance; the angle was 10° ± 13°. The methodology in the present study confirmed the possibility of locating the exact insertion of the CFL, in spite of previously reported difficulties.

5.2.3 Calcaneofibular Ligament (CFL) Dimensions

CFL length in the current study is in agreement with most of those reported previously (Table 5.3), except for Apoorva et al. (2014) which was shorter; additionally Yıldız and Yalcın (2013) reported shorter and longer length of the CFL being 15 mm and 20 mm respectively. Although the methodologies employed in measuring length were not always clear, including measuring the ligament's longest fibres (Burks and Morgan, 1994), MRI measurement from the mid proximal to mid distal attachments (De Asla et al., 2009), considering the free borders of the insertion points (Kitsoulis et al., 2011) and measuring the ligament's free length (Milner and Soames, 1998a). The length observed in the current study disagrees with Testut and Latarjet (1948), Milner and Soames (1998a), Raheem and O'Brien (2011) and Luo et al. (1997), probably due to methodology differences, but also possibly due to the position of the ankle joint when taking the measurement: ligament length may be shorter or longer in relation to ankle joint position; therefore, their reported findings may not be comparable with the findings of the current study. In the current study CFL length was significantly longer in males compared to females probably due to their longer feet; further support for this is that foot length and 1st metatarsal length were both positively correlated with CFL length. Knowing the CFL length may provide a better understanding of the distance between the proximal fibular and distal talar bony attachments; this may help in knowing the appropriate length of the ligament that is required functionally to provide the necessary stability and support.

Table 5.3 CFL length reported in previous studies compared to the current study: NK; not known.

Study	N	Length (mm)	Study	N	Length (mm)
Testut and Latarjet, 1948; as cited by Milner and Soames, 1998a	NK	30 – 40	Siegler et al., 1988	20	27.69 ± 3.3
Buzzi et al., 1993	10	24.3	Sarrafian, 1993a	NK	30
Burks and Morgan, 1994	39	35.8	Luo et al., 1997	11	20.6 ± 2.9
Milner and Soames, 1998a	40	19.5 ± 3.9	Sindel et al., 1998	24	26.8 ± 4.91
Ozeki et al., 2002	12	29.9 ± 4.24	Taser et al., 2006	42	31.94 ± 3.68
De Asla et al., 2009	4	28 ± 2.9 (MRI)	Uğurlu et al., 2010	22	26.67
Boonthathip et al., 2011	10	31 ± 6 (MRI)	Kitsoulis et al., 2011	72	31.83
Raheem and O'Brien, 2011	20	18.5 ± 6.3	Neuschwander et al., 2013	8	24.8 ± 2.4
Apoorva et al., 2014	60	27 ± 3.89	Haytmanek et al., 2015	11	28.1 ± 4.8 (lateral radiography) 24.5 ± 4.5 (mortise view)
Current Study	**63**	**30.18 ± 5.03**			

CFL width was 4.19 ± 1.55 mm, again similar to the range in previous studies (Table 5.4), except for Buzzi et al. (1993), Sindel et al. (1998) and Raheem and O'Brien (2011), which were wider. The wider CFL widths might have occurred due to measurement including other tissues, such as the LTCL which was observed to blend anteriorly in many cases in the present study. Furthermore, width measurement was not clearly explained in many previous studies, particularly the level at which the width was measured.

Table 5.4 CFL width reported in previous studies compared to the current study: NK; not known.

Study	**N**	**Width (mm)**	**Study**	**N**	**Width (mm)**
Testut and Latarjet, 1948; as cited by Milner and Soames, 1998a	NK	4 – 5	Ruth, 1961	75	4 – 6
Buzzi et al., 1993	10	6.7	Sarrafian, 1993a	NA	5
Burks and Morgan, 1994	39	5.3	Milner and Soames, 1998a	40	5.5 ± 1.6
Sindel et al., 1998	24	6 ± 0.8	Taser et al., 2006	42	4.68 ± 1.34
Uğurlu et al., 2010	22	4.57	Boonthathip et al., 2011	10	4.6 ± 1 (MRI)
Kitsoulis et al., 2011	72	4.42	Raheem and O'Brien, 2011	20	7.5 ± 3.5
Yıldız and Yalcın, 2013	45	5.44 ± 2.34	Apoorva et al., 2014	60	5.5 ± 1.12
Current Study	**63**	**4.19 ± 1.55**			

In the current study, CFL proximal and distal width were 4.3 ± 1.4 mm and 6.89 ± 1.77 mm respectively, with proximal width differing from that reported by Taser et al. (2006) (7.19 ± 2.23 mm) and Buzzi et al. (1993) (6.7 mm), while distal width was inconsistent with Taser et al. (2006) (9.68 ± 1.73 mm). A possible cause for these discrepancies could be the small sample size (n = 10) in Buzzi et al. (1993) or the involvement of surrounding tissue at the proximal or distal attachments, where thick fibrous tissues and the LTCL may blend with the

CFL, as well as the presence of connecting fibres with the ATFL proximally. In the current study the CFL distal width was positively correlated with both proximal and mid width, with distal width being significantly wider than proximal and mid width, thus agreeing with Taser et al. (2006). Having a wider insertion on the calcaneus may help provide better support distally. Although foot side had no effect on any CFL dimensions, except distal width, it was somewhat surprising to find that the CFL on the left feet (7.51 ± 1.86 mm) was wider than that on the right feet (6.26 ± 1.44 mm). Yıldız and Yalcın (2013) reported differences in right and left CFL widths, being 5.25 ± 2.79 mm and 5.64 ± 1.73 mm respectively, as did Apoorva et al. (2014) - 5.55 ± 0.17 mm on the right and 5.33 ± 0.26 mm on the left.

The current study found CFL thickness at its midpoint to be 1.40 ± 0.48 mm, which agrees with Butler and Walsh (2004) (1.5 ± 0.2 mm), (Hua et al. (2008) (1.52 ± 0.21 mm), (Kitsoulis et al., 2011) (1.58 mm) and (Apoorva et al., 2014) (1.65 ± 0.43 mm). However other studies have reported significantly thicker CFLs: 3 mm (Ahmad et al., 1998; Sarrafian, 1993a) and 2.13 ± 0.5 mm (Dimmick et al., 2008). Both Dimmick et al. (2008) and Ahmad et al. (1998) measured CFL thickness from MRI scans which may explain this finding, while Sarrafian (1993a) did not state sample size or how the thickness was measured; therefore these findings may not be comparable to the findings of the current study.

Dimensional measurements of the different ligaments using radiography or MRI represented different results compared to direct measurements in many cases. There are a number factors that may affect measurements using MRI which include: MRI sequence, thickness of the MRI slice, and segmentation method, as well as the software that was used in interpreting the measurements from the MRI images (Stephen Gandy, personal communication, 24 March 2016). Therefore, dimensional measurements of the same specimens using both direct measurements as well as MRI measurement is recommended to enable better comparison and define any variability. In addition, another factor that may contribute to these differences is the nature and number of the specimens that have been used. For instance, Ahmad et al. (1998) and Dimmick et al. (2008) measured the thickness using MRI on 19 and 21 ankles from living individual respectively; while De Asla et al. (2009) used MRI to measure the length in 4 normal male ankles.

5.2.4 CFL Bony Attachment Lengths

The current study found that 10.45% of CFL length was attached proximally to the fibula, with the mean length being 3.11 ± 2.56 mm. Two previous studies reported the CFL PBA as the proximal/distal dimension of the proximal attachment, being 6.8 ± 1.4 mm (Sindel et al., 1998) and 8.2 mm (Burks and Morgan, 1994): both much greater than in the present study. The difference might be due to different methods of determining the last bony attachment point, which may blend proximally with the ATFL attachment as demonstrated by Burks and Morgan (1994); however, their methodology was far from clear in this regard. The distal bony attachment length (DBA) of the CFL comprised 28.75% of the total CFL length being 8.56 ± 2.54 mm, which is approximately three times longer than the CFL PBA. The distal bony attachment length in the current study was similar to that of Sindel et al. (1998) (7.7 ± 1.15 mm) and Burks and Morgan (1994) (10 mm). The CFL had 60.80% of its length free (18.1

± 4.07 mm) with no bony attachment (NBA) to either the fibula or calcaneus: this agrees with the CFL length reported by Milner and Soames (1998a) (19.5 ± 3.9 mm). However, it is significantly less than the free length (27 ± 3.89 mm) reported by Apoorva et al. (2014).

CFL PBA, NBA and DBA were all positively correlated with CFL length. The positive correlation between the CFL PBA and CFL proximal attachment distance to the lateral malleolar tip suggests that the longer the proximal attachment the longer the distance to the lateral malleolar tip: this is to be expected since a longer proximal bony attachment requires the ligament to originate further superiorly, accordingly the distance to the tip will be increased. There was also a positive correlation between CFL length and the distance to the lateral malleolar tip, as well as to the CFL PBA. CFL NBA was longer in males (20.3 ± 4.48 mm) than females (16.75 ± 3.18 mm), which was anticipated as CFL length was significantly longer in males compared to females, as was foot length and 1st metatarsal length. This explains the positive correlations between the CFL NBA and foot length and 1st metatarsal length.

5.2.5 Relations to Different Ligaments and Bands

Connecting fibres between the CFL proximal origin and the PTFL in the malleolar fossa were observed in many cases, agreeing with Buzzi et al. (1993) who reported the CFL originating proximally from the lateral malleolus anterior to the tip and extending to the malleolar fossa. There have also been reports indicating a blending of the proximal attachments of the CFL and ATFL

(Apoorva et al., 2014; Burks and Morgan, 1994; Sarrafian, 1993; Wiersma and Griffioen, 1992): this is discussed in the anatomy of the ATFL section. Furthermore, the IATFL in the two band form leaves the CFL proximally 3.91 ± 1.74 mm distal to the CFL origin. Buzzi et al. (1993) reported that the LTCL is deep to the CFL and may blend with it: this is in keeping with the current study as close to the CFL origin there was 5 mm of blending with the LTCL in 22.22% of specimens. In addition, the LTCL distal attachment blended for 7.73 mm with the CFL in 72.73% of specimens.

Kitsoulis et al. (2011) reported the two (22.2%) and three (5.6%) band forms of the CFL: this disagrees with most previous investigations (Raheem and O'Brien, 2011; Golano et al., 2010; van den Bekerom et al., 2008; Milner and Soames, 1998a). In the current study fibre fasciculation superficially was seen but did not constitute independent bands, except in two cases where an additional independent band was observed. In one specimen an additional anterior band was observed originating anterior to the lateral malleolar tip and inserting into the calcaneal lateral surface blending distally with the anterior part of the CFL; In the other specimen an additional posterior band was observed attaching proximally to the lateral malleolus, but posterior to the lateral malleolar tip, descending to insert distally into the calcaneal lateral surface as well as the posterior portion of the CFL. Kitsoulis et al. (2011) suggest that the number of CFL bands, as in the current study, should be considered in future investigations. It is possible that these additional independent bands could have been missed or sectioned in other studies, including the current study, due to the complicated anatomy of the surrounding tissues, fat, fibularis tendons and vessels as they blend with thick layers of soft tissue and the fibular retinaculum.

Additionally, Kitsoulis et al.'s (2011) investigation was conducted in Greece using specimens that had no record of age or gender. One further explanation is that the dissection revealed the CFL in all previous studies as a single band structure based on previous studies sectioning or removing the fibular retinaculum aggressively, thereby leading to these additional bands being missed. The additional anterior band might be confused with the LTCL, which is primarily attached to the talus but descends to the calcaneus. Future studies are recommended to pay attention to the surrounding area of the CFL. Additional bands may change the understanding of CFL function, as well as its surgical repair and reconstruction.

5.3 Anatomy of the Posterior Talofibular Ligament (PTFL)

5.3.1 Proximal Attachment of the Posterior Talofibular Ligament (PTFL)

The PTFL proximal attachment attached to the medial aspect of the lateral malleolus from the inferior part of the malleolar fossa, thus agreeing with previous reports (Gursoy et al., 2015; Clanton et al., 2014; Boonthathip et al., 2011; Taser et al., 2006; Sindel et al., 1998). The origin was 9.75 ± 1.61 mm from the lateral malleolar tip: this is consistent with previous studies that reported the distance as 8.2 ± 1.43 mm (Sindel et al., 1998) and 9.7 mm (Burks and Morgan, 1994). However, it disagrees with Clanton et al. (2014) (4.8 mm) and Wenny et al. (2014) (10.45 ± 3.08 mm). In some studies, the methodology used to measure the distance to the tip was not clear; in the current study the distance was measured from the middle proximal point of the PTFL origin to the malleolar tip along an oblique line after releasing the deltoid ligament medially and revealing the whole proximal insertion of the ligament. In addition, both Clanton et al. (2014) and Wenny et al. (2014) had smaller sample sizes (n= 14 and 17 respectively) compared to the current study (n = 45). In the current study males had a significantly greater distance (10.52 ± 1.72 mm) compared to females (9.2 ± 1.3 mm), which is probably due to the larger foot size in males and a larger fibula.

5.3.2 Distal Attachment of the Posterior Talofibular Ligament (PTFL)

Distally, the PTFL had a long attachment to the talus which started on the posterior part of the lateral surface of the talus, agreeing with Taser et al. (2006), then continued on the posterior surface of the talus, being consistent with previous reports (Wenny et al., 2014; Hua et al., 2008; Burks and Morgan, 1994). Clanton et al. (2014) reported the PTFL distal attachment to end lateral to the talar posterolateral tubercle: in the current study this was observed in 23.2% of specimens, while in the remaining 76.8% it ended by inserting lateral and superior to the posterolateral tubercle or os trigonum (if it existed). It is noted that Clanton et al. (2014) had a smaller sample size (n = 14) than the present study (n = 68), which may account for the difference between the two studies.

Boonthathip et al. (2011) reported that the PTFL had two bands, anterior and posterior. In the current study the PTFL did not have two independent bands, rather it was a thick wide ligament with the deep anterior part inserting into the posterolateral aspect of the talus and the superficial posterior part inserting lateral or superolateral to the talar posterolateral tubercle. This observation is consistent with Gursoy et al. (2015), who reported the PTFL consisting of anterior and posterior parts: furthermore, it agrees with Courvoisier et al. (2008) who demonstrated that the PTFL has long posterior and short anterior groups of fibres.

5.3.3 Posterior Talofibular Ligament (PTFL) Dimensions

In the current study, PTFL dimensions were measured using two methods: with the ankle intact in the neutral position and after dislocating the ankle medially, revealing the hidden proximal part of the ligament in order to measure its true (total) length; this length has not been demonstrated in previous investigations. This length is longer than that usually measured while the ankle is intact, as it includes the proximal part of the ligament situated posterior to the posterior surface of the distal fibula. The methodology in the current study provided measurement of the PTFL length while extended, involving the true proximal and distal points of insertion. Table 5.5 shows PTFL length in previous studies, as well as in the present study. However, it should be noted that in previous studies, it was not clear whether the values reported were for the observed length while the ankle was intact, or total length with the revealed part. Milner and Soames (1998a) highlighted the difficulty of measuring the total (true) length of the ligament due to its attachment to the posterolateral surface of the talus.

The true length in the current study is similar to those in Table 5.5, except for Luo et al. (1997), Sindel et al. (1998) (embalming method not known), Haytmanek et al. (2015), Sarrafian (1993a) and Wenny et al. (2014). Haytmanek et al. (2015) used radiography (miniature fluoroscopy) to measure the length from frozen specimens, thus possibly explaining the difference with the direct measurement, while Sarrafian (1993a) did not explain the methodology used. In the current study, PTFL length that was measured with the ankle intact was in a close agreement with Siegler et al. (1988) (frozen specimens), Buzzi et al. (1993) (formalin embalmed) and Taser et al. (2006) (unknown embalming), as well as with Haytmanek et al. (2015) who used radiography in the mortise view. However, it disagrees with all other studies in Table 5.5. Furthermore, Ozeki et al. (2002) (frozen specimens) and Uğurlu et al. (2010) (formalin embalmed specimens) had small sample sizes (12 and 22 specimens respectively), whereas in the present study the sample size was 57. The reported length by Wenny et al. (2014) (formalin embalmed specimens) and Luo et al. (1997) was smaller than both PTFL true length and the length in neutral in the current study: their sample sizes were 17 and 11 respectively; additionally the embalming method of the specimens used in Luo et al.'s (1997) study was not mentioned. On the other hand, Sindel et al. (1998) reported PTFL length as 41 ± 2.81 mm, significantly larger than the current study and previous studies. The total PTFL length in males was greater (26.44 ± 2.76 mm) than in females (22.38 ± 3.08 mm), being supported by the positive correlation between PTFL length and foot and 1st metatarsal length. Longer PTFL lengths also had a wider proximal width attachment.

Table 5.5 Reported PTFL length in previous studies compared to the current studyNK; not known.

Study	N	Length (mm)	Study	N	length (mm)
Siegler et al., 1988	20	21.16 ± 3.86	Sarrafian, 1993a	NK	30
Buzzi et al., 1993	10	21.9	Burks and Morgan, 1994	39	24.1
Luo et al., 1997	11	14.2 ± 2.8	Milner and Soames, 1998a	40	23 ± 7
Sindel et al., 1998	24	41 ± 2.81	Ozeki et al., 2002	12	23.7 ± 3.1
Taser et al., 2006	42	21.66 ± 4.84	Uğurlu et al., 2010	22	24.12
Boonthathip et al., 2011	10	27.8 ± 3.6 (MRI)	Wenny et al., 2014	17	16.41 ± 2.58 - 17.38 ± 2.34
Haytmanek et al., 2015	11	10.5 ± 2 (lateral view), 19.5 ± 2.5 (mortise view) (Radiography)	**Current study**	**59**	**24.03 ± 3.55 (Total length); 21.16 ± 2.74**

Difficulties in measuring the width of the PTFL have been reported due the course of the ligament attaching the talus. Burks and Morgan (1994) also demonstrated that the ligament width may change in different joint positions. In the current study width was measured after dislocating the ankle medially thereby exposing the whole ligament, following which width was determined at proximal, middle and distal points. Table 5.6 shows the reported PTFL width in previous studies compared to the present study. The current study found that the directly measured width (5.52 ± 1.64 mm), was similar to previous studies, except Boonthathip et al. (2011) who reported a larger mean width, which could be due to taking measurements from MRI scans.

Table 5.6 Reported PTFL width in previous studies compared to the current study.

Study	N	Width (mm)	Study	N	Width (mm)
Ruth, 1961	75	6	Milner and Soames, 1998a	40	5.5 ± 2.5
Sindel et al., 1998	24	6.1 ± 0.77	Taser et al., 2006	42	5.55 ± 1.25
Uğurlu et al., 2010	22	5.09	Boonthathip et al., 2011	10	8.7 ± 3 (MRI)
Wenny et al., 2014	17	4.74 ± 1.15 - 5.09 ± 1.31	**Current study**	**60**	**5.52 ± 1.64**

In the current study the proximal width was 7.1 ± 1.72 mm, which is inconsistent with the Sarrafian (1993a) (5 mm) and Buzzi et al. (1993) (10.5 mm). Distal PTFL width in the present study (6.48 ± 2.05 mm) was significantly wider than middle width and has not been previously reported. The proximal and middle width in males (7.82 ± 1.8 mm and 4.97 ± 1.43 mm) were significantly wider compared to females (6.64 ± 1.52 mm and 4.97 ± 1.43 mm). Although distal width was not correlated with PTFL length or middle width, proximal width showed positive correlations with both PTFL length and middle width: this could be due to its long attachment to the talus.

The thickness of the PTFL was 2.06 ± 0.62 mm in the current study, which is similar to Butler and Walsh (2004) (2.3 ± 0.6 mm). However, it is inconsistent with Sarrafian (1993a) (5 – 8 mm), who did not clarify the technique used to measure thickness, which led to difficulty in comparing the two studies. Thickness in the current study was measured at the middle point in a superior/inferior direction which is consistent with the ligament orientation when viewed posteriorly.

5.3.4 Posterior Talofibular Ligament (PTFL) Bony Attachment Lengths

The present study found that 15.13% and 58.04% of the PTFL total length had a proximal attachment to the malleolar fossa of the fibula and a distal attachment to the talar posterolateral surface respectively: 26.82% of the ligament therefore had no bony attachment. The proximal bony attachment length was 3.65 ± 2.31 mm, which contrasts with previous reports of 6.9 ± 0.69 mm (Sindel et al., 1998) and 6.9 mm (Burks and Morgan, 1994): in both these studies the method of considering and measuring the proximal bony attachment was not clear; therefore their results may not be comparable with the findings of the current study. The no bony attachment length (NBA) of the PTFL was 6.47 ± 2.25 mm: this has not been previously reported.

The distal bony attachment length (DBA) was 14 ± 4 mm, differing from Ruth (1961) and Sindel et al. (1998) who reported it as 9 mm and 20.7 ± 2.15 mm respectively. Again the difference might be due to different considerations of the end of the distal fibres. Sindel et al. (1998) disagrees with PTFL length in the current study and earlier investigations. In the current study the DBA was significantly greater in males (15.79 ± 3.45 mm) compared to females (12.8 ± 3.94 mm) and is probably explained by the DBA comprising the majority of the PTFL length, which was greater in males. Further support to this is given by the positive correlation between the DBA and PTFL length, foot length and 1st metatarsal length.

5.4 Anatomy of the Medial Collateral Ligaments (MCL; Deltoid)

An injury to the deltoid ligament may not be considered by clinicians in patients with chronic ankle instability, although 72% of such cases show MRI evidence of an injury to the deltoid (Crim et al., 2011). The morphology of the deltoid ligament has been variably reported in the literature, which may lead to misdiagnosing an injury to this complex structure. Sound anatomical knowledge (Golanó et al., 2010) of the medial collateral complex is therefore important for successful reconstruction (Cromeens et al., 2015).

5.4.1 Components of the Medial Collateral Ligaments

In the current study, both the anterior and posterior borders of the deltoid were attached to the joint capsule, which is in agreement with Sarrafian (1993a). Previous studies agree that the deltoid ligament consists of superficial and deep layers (Campbell et al., 2014; Boss and Hintermann, 2002; Milner and Soames, 1998a; Milner and Soames, 1998b; Pankovich and Shivaram, 1979a); however, there is disagreement concerning the different components (bands). Early descriptions of the deltoid components were published between 1822 and 1961 and demonstrated disagreement in defining the various parts. Later more detailed investigations were conducted, but they also showed inconsistencies: therefore, there was a need for a comprehensive detailed morphological study of deltoid.

The current study agrees with Campbell et al. (2014), Panchani et al. (2014), Boss and Hintermann (2002) and Milner and Soames (1998a, 1998b) who reported six components of the deltoid ligament, including the tibionavicular

(TNL), tibiocalcaneal (TCL), tibiospring (TSL), superficial tibiotalar (STTL) (superficial layer), deep posterior tibiotalar (PTTL) and deep anterior tibiotalar (ATTL) ligaments (deep layer). This is, however not consistent with the majority of anatomy textbooks which state that the deltoid is composed of four bands: TNL, TCL, PTTL and ATTL (Drake et al., 2010a; Moore et al., 2010; Standring, 2008; Palastanga et al., 2006; Norkus and Floyd, 2001; McMinn et al., 1996). However, Pankovich and Shivaram (1979a) state that all bands are components of the deltoid with the exception of the tibiospring ligament, which might be considered part of the TCL.

The components of the deltoid observed in the current study disagrees with Cromeens et al. (2015), who limited it to the STTL, PTTL, ATTL, the inferoplantar longitudinal ligament and considered the three anterior parts of the superficial deltoid (TNL, TSL and TCL) as a single band called the tibiocalcaneonavicular ligament. However, the different parts of the tibiocalcaneonavicular ligament have different orientations and distal attachments, which leads the current study to consider each part separately and to act differently in different movements of the ankle and subtalar joints. Cromeens et al. (2015) considered the inferoplantar ligament part of the deltoid ligament, although it was considered part of the spring ligament by Vadell and Peratta (2012). Furthermore, Hintermann and Golano (2014) demonstrated the spring (plantar calcaneonavicular) ligament to be part of the deltoid ligamentous complex; however, the spring ligament is a plantar ligament and has no attachment to the medial malleolus to which all other parts of deltoid share a proximal attachment; therefore their finding is not acceptable.

The ATTL, TNL, TCL, PTTL, STTL, fibres to the spring ligament, a band deep to the TCL (dTCL) and a band posterior to the sustentaculum tali (PST) were the eight parts of deltoid reported by Panchani et al. (2014). Fibres to the spring ligament are consistent with the TSL in the current study, while the band posterior to the sustentaculum tali (PST), as shown in Figure 2.40 and found in 6% of specimens, appears to be similar to the STTL in the present study as it has the same orientation as the STTL as well as its relation to the TCL, sustentaculum tali and PTTL. Moreover, the dTCL as reported by Panchani et al. (2014), seen in 12% of specimens, is equivalent to the anterior band of the PTTL in the current study. This was confirmed as it had a similar orientation and attachments points.

These inconsistencies may be the result of the deltoid ligament consisting of multidirectional bands with four bony attachments spanning 3 joints, thus it is unlike other ligament in the body (Cromeens et al., 2015). Another factor could be that the different parts of the MCL fuse and blend together (Palastanga et al., 2006; McMinn et al., 1996), with Sarrafian (1993) suggesting that the different MCL fibres, their features and strength has resulted in their acceptance as ligaments. However, defining these bands is artificial, as it can only be done by considering their distal insertions (Sarrafian, 1993). In the current study, the different parts of the deltoid ligament were observed to blend with other bands as well as being separated at different levels. The criteria used in the present study to identify the different bands of the deltoid ligament were their orientation, distal attachments, partial separation and response in different joint positions.

5.5 Superficial Layer of the Medial Collateral Ligaments (Deltoid)

The superficial layer of the deltoid ligament consists of four bands from anterior to posterior, the tibionavicular (TNL), tibiospring (TSL), tibiocalcaneal (TCL) and superficial tibiotalar ligaments (STT): this agrees with Panchani et al. (2014). Sepúlveda et al. (2012) reported that the shape of the superficial layer of the deltoid was trapezoidal (70.4%), rectangular (18.5%) or triangular (11.1%): in the current study it was irregular but mainly trapezoidal. The shape of the superficial layer will affect the coverage of the deep layer, but nevertheless it has a role in resisting tensile forces. In the current study the ATTL was always covered by the superficial layer, while the PTTL had different coverings (discussed later). Campbell et al. (2014) observed adipose tissue between the superficial and deep layers of deltoid: this was also seen in the present study, but in addition small fibres passed between them, connecting the two layers. Sepúlveda et al. (2012) reported that superficial deltoid was continuous and did not possess any fasciculation; however, the criteria used in defining the different parts have already been stated and supported by a number of studies.

Pankovich and Shivaram (1979a) reported that the proximal attachment of the superficial deltoid was to the anterior and posterior colliculi of the medial malleolus, while Sepúlveda et al. (2012) indicated that this layer extended to the inferior border of the medial malleolus. These descriptions are not very precise: in the current study this layer was observed to attach proximally to the anterior and medial surfaces of the anterior colliculus, as well as to the medial surface of the medial malleolus superior to the edge of the intercollicular groove, being anterior to the posterior colliculus.

Variations in the distal attachment of the superficial layer of the deltoid ligament have also been reported. The current study found that the superficial layer had a very wide and complex attachment, including to the navicular, spring ligament, talar medial surface, calcaneus, sustentaculum tali and the talar posteromedial tubercle. This observation disagrees with both Pankovich and Shivaram (1979a) and Wenny et al. (2014) who did not observe an attachment to the spring ligament or talar medial surface. Furthermore, Sepúlveda et al. (2012) and Wenny et al. (2014) did not observe an attachment of the superficial layer to the talar medial surface or posteromedial tubercle. In the current study, careful dissection was conducted to expose the distal bony attachment of the ligament: the above differences are probably due to the dissection techniques used, as well as not following all parts of the superficial deltoid distally to locate the final distal attachments. Sepúlveda et al. (2012) determined the dimensions of the superficial layer as a single complex structure without considering the different borders of the superficial parts. In the current study, each individual part or band was studied and measured independently to provide detailed morphological data on the parts that had different distal attachments and orientations.

5.5.1 Tibionavicular Ligament (TNL)

The TNL was a consistent part of deltoid, thereby agreeing with Campbell et al. (2014), Panchani et al. (2014) and Milner and Soames (1998b). Panchani et al. (2014) demonstrated that it had an attachment to the joint capsule, but that it was possible to separate them in 89% of specimens; however Boss and Hintermann (2002) indicated that the TNL was a fibrous layer of the joint capsule rather than being a discrete band or ligament. In the present study the

TNL could be separated from the joint capsule and therefore defined as a band in all specimens; therefore, Boss and Hintermann (2002) finding is not acceptable. The inconsistency in findings might be due to the TNL being thin and blending with the joint capsule, as well as having a wide attachment to different sites, as discussed later.

The TSL was continuous with the TNL in 86% of specimens in the current study, in contrast to Pankovich and Shivaram (1979a) who reported the TNL being continuous with the TCL: they did not consider the TSL as a part of deltoid and perhaps considered the TSL as part of either the TNL or TCL. The current study showed that the posterior border of the TNL was partly covered by the superficial fibres of the TSL in 32.7% of specimens.

5.5.1.1 Proximal and Distal Attachments of the Tibionavicular Ligament (TNL)

Panchani et al. (2014) reported the TNL proximal attachment being to the medial malleolus, while Milner and Soames (1998b) demonstrated it to be to the anterior border of the anterior colliculus of the medial malleolus. This latter attachment was observed in 94% of specimens in the current study, while in 6% it attached proximally to both the anterior border and medial surface of the anterior colliculus.

In the current study, the TNL had a wide and complex distal attachment inserting into the dorsomedial surface of the navicular, thus agreeing with previous studies (Panchani et al., 2014; Palastanga et al., 2006; Pankovich and Shivaram, 1979a). In addition the distal insertion extended to blend with the spring ligament or its connecting fibres, as reported by Palastanga et al. (2006). Furthermore, in 88.3% of specimens in the current study part of the TNL deep fibres attached to the talar medial surface as far as to the talar neck, which is in agreement with Milner and Soames (1998b). However Milner and Soames (1998b) considered that this part of the TNL attached to the talus was an individual band. In addition, Sarrafian (1993a), citing Beau (1939), reported that the deep fibres from the anterior superficial tibiotalar ligament and TNL inserted into the dorsal side of the talar neck posterior to the head of the talus, calling this the anterior superficial tibiotalar ligament, while the superficial fibres inserted into the dorsomedial part of the navicular, i.e. the tibionavicular ligament. In addition, Beau (1939) reported that these parts of the TNL overlap and mix, except where fibres only attach to the talus and do not extend to the navicular: this was confirmed in the present study; however the talar part was not completely distinct from the superficial main part of the TNL.

5.5.1.2 Tibionavicular Ligament (TNL) Dimensions

In the current study TNL length was 34.16 ± 5.72 mm, which is close to that of Luo et al. (1997) (32.5 ± 4.7 mm), but less than that of Siegler et al. (1988) (41.83 ± 4.93 mm), whose length was taken from the anterior, posterior lateral and medial borders of the ligament, while the length in the current study was taken along the longest fibres with the ankle in neutral. Due to the complex shape of the TNL Milner and Soames (1998a) reported the length of the TNL as 28.5 ± 5.9 mm (anterior border) and 15.5 ± 4.4 mm (posterior border): their anterior border length is closer to the observations of the current study as the anterior border is longer because the ligament crosses to insert distally onto the dorsomedial surface of the navicular. In the current study, TNL length was significantly greater in males (36.85 ± 6.75 mm) compared to females (32.15 ± 3.84 mm), probably being due to foot size in males being larger than in females. Further support is provided by the fact that TNL length was positively correlated with both foot length and 1st metatarsal length. In addition, right feet had a longer TNL (36.27 ± 5.76 mm) compared to the left (32.25 ± 5.08 mm): there is no obvious reason for this difference, although a possible reason is that the right side is the dominant side in most people.

The TNL proximal, middle and distal widths were 4.8 ± 2.22 mm, 12.58 ± 3.06 mm and 9.5 ± 2.88 mm respectively: greater widths were reported by Milner and Soames (1998a), being 11 ± 3.8 mm, 13.5 ± 5.4 mm and 27.5 ± 10.3 mm respectively. There is no obvious reason for this disagreement; however, the difference in middle width is not as great as for the proximal and distal width: proximal width was limited mostly to the anterior border of the anterior colliculus, which was smaller in the current study. In addition, distal TNL width in the current study was measured as it attached to the navicular.

Middle width was significantly greater than both proximal and distal width, with statistical analysis showing middle width was positively correlated with proximal and distal width. This could be due to the shape of the ligament as it expands from its proximal to distal attachments.

In the current study TNL thickness was 0.62 ± 0.28 mm, being much less than the only other reported thickness of 1.6 mm (Mengiardi et al., (2007), who measured thickness from MRI, which may explain the difference.

5.5.1.3 Tibionavicular Ligament (TNL) Bony Attachment Lengths

While Campbell et al. (2014) determined the footprint area of the TNL tibial and navicular attachments, there have been no reports of the TNL bony attachment lengths. The TNL was complex in the way that it attached to different bony sites; therefore, different bony attachment lengths are presented for the TNL compared to other ligaments in this study; this has not been previously reported.

5.5.2 Tibiospring Ligament (TSL)

The tibiospring ligament (TSL) was a consistent band of the deltoid ligament, agreeing with Boss and Hintermann (2002) and Milner and Soames (1998b), but not with others (Cromeens et al., 2015; Drake et al., 2010a; Moore et al., 2010; Standring, 2008; Palastanga et al., 2006; Norkus and Floyd, 2001; McMinn et al., 1996; Pankovich and Shivaram, 1979a). This contradiction may be due to considering the TSL as a part of the TCL or as part of the three bands known as the tibiocalcaneonavicular ligament (TNL, TCL, TSL), as reported by Cromeens et al. (2015). In addition, Sarafian (1993a) called the TSL the tibioligamentous fascicle and Panchani et al. (2014) fibres to the spring ligament: the latter reporting had a successful separation of the TSL from the TCL in 15 of 33 specimens. In the current study the TSL was easy to define from the TCL, although they had attachments to each other; however, the TSL continued with the TNL anteriorly in 84.3% of specimens. In 3.2% of specimens some TNL fibres of the posterior part overlapped the TSL, while the TSL was continuous with the superficial fibres of the TNL and did not extend to the deep fibres. Milner and Soames (1998b) stated that the TSL was the most superficial component of the deltoid ligament. This was confirmed in the current study in relation to the TCL, STTL and the deep layer; however, the TNL was also superficial to these bands. In the current study the TSL was fully continuous with the TCL in 6.5% of specimens, while in 84.8% and 8.7% it was partly continuous and completely separated from the TCL respectively.

5.5.2.1 Proximal and Distal Attachments of the Tibiospring Ligament (TSL)

The TSL proximal attachment was between the TCL and TNL attachments agreeing with Panchani et al. (2014) and Campbell et al. (2014), who reported the attachment being superior and posterior to the TNL. Sarrafian (1993a) observed that the TSL was attached proximally to the anterior aspect of the anterior colliculus of the medial malleolus: this was also observed in the present study, but only in 17% of specimens. The majority of specimens (60.4%) had a proximal attachment to both the anterior border and medial surface of the anterior colliculus: other attachments were to the medial surface of the anterior colliculus only (20.8%) and to the anterior and medial aspects of the anterior colliculus, as well as the medial surface of the medial malleolus superior to the edge of the intercollicular groove (1.9%).

Panchani et al. (2014), Milner and Soames (1998b), Klein (1994) and Sarrafian (1993a) state that the TSL attached distally to the spring ligament: this was confirmed in the current study, but was only seen in 15% of specimens. The majority (78.3%) had a distal attachment to both the spring ligament and sustentaculum tali. Furthermore, it had a distal attachment to the sustentaculum tali only in 6.7% of specimens. A more precise description of the attachment of the TSL to the sustentaculum tali was made in the current study, being to its superior (72.1%), anterosuperior (23.3%) and superoposterior (4.7%) surfaces.

5.5.2.2 Tibiospring Ligament (TSL) Dimensions

TSL length (31.48 ± 6.41 mm) in the present study was longer than in previous reports: 18.5 ± 6.3 mm (Milner and Soames, 1998a), 18.59 ± 4.37 mm (Siegler et al.,1988), 24.3 ± 4 mm (Boss and Hintermann, 2002) and 25 mm (Campbell et al., 2014). The differences may be linked to the determination of the proximal and distal TSL attachments, which given the complexity of the wide distal part of the ligament blending with the spring ligament is difficult. Siegler et al. (1988) considered the ligament borders in measuring the length, while other studies did not clearly state the methodology used, leading to difficulty in comparing results in the current study. In the present study TSL length was measured from the most proximal end of the attachment to the level where the ligament reached the sustentaculum tali, or blended with the connecting fibres of the spring ligament. Males (35.36 ± 6.51 mm) had a longer TSL compared to females (28.97 ± 5.02 mm): again this is probably due to the longer feet of males, which is further supported by the positive correlation between TSL length and both foot length and 1st metatarsal length. Furthermore, longer ligaments were wider proximally, in their middle and distally.

The current study found proximal, middle and distal widths of 5.08 ± 2.22 mm, 5.64 ± 1.57 mm and 8.08 ± 2.57 mm respectively. The proximal and middle widths disagree with those reported by Milner and Soames (1998a), but the distal width is within their reported range. Campbell et al. (2014) measured width at the spring ligament junction as 5.9 mm, smaller than the distal width reported here. This could be because the distal spring junction might be inferior to the sustentaculum tali leading to measuring the width of the attachment to the spring ligament and not to the sustentaculum tali. Distal width was significantly the widest and when there was attachment to the sustentaculum tali was 5.32 ± 2.2 mm, being positively correlated with foot length, ligament length, proximal and middle width, and ligament thickness. The thickness in the current study was 0.79 ± 0.3 mm, which is less than that determined as 1.5 ± 0.5 mm which was reported by Boss and Hintermann (2002): there is no obvious reason for this difference. TSL thickness measured from MRI scans was 2 mm (Mengiardi et al., 2007), much more than either of the above. An interesting observation in the current study was that both distal width and TSL thickness were negatively correlated with age, suggesting that either degeneration or natural age-related changes may cause the ligament to lose fibres leading to a diminished distal width and thickness. This poses questions such as: what is the effect of ageing on the function of the ligament? Does ageing increase the vunerability of the ankle ligaments to injury due to the loss of ligament fibres leading to a decrease in thickness? However, this should be investigated in further studies using specimens from different age groups; in the current study the age of the cadavers ranged between 68 and 98 years. In addition, age should be considered in studies that investigate factors causing ankle ligament injuries, the superficial deltoid in particular.

5.5.2.3 Tibiospring Ligament (TSL) Bony Attachment Lengths

In the current study, the TSL proximal bony attachment length (5.84 ± 3.01 mm) and the free or no bony attachment length (20.4 ± 4.55 mm) comprised 17% and 59.37% of TSL total length respectively. The distal part of the TSL may not end by attaching to bone, but may continue distally to blend with fibres that connect to the spring ligament. The distal attachment length (or the length of blending with the spring ligament) was 8.13 ± 3.47 mm comprising 23.66% of TSL length. The bony attachment lengths and the free length have not been previously reported; however, both Campbell et al. (2014) and Boss and Hintermann (2002) reported a proximal attachment area. In addition, Boss and Hintermann (2002) also reported the distal attachment area. However, the bony attachment lengths, as well as the proximal, middle and distal width are reliable measurements, as well as being easier to obtain.

5.5.3 Tibiocalcaneal Ligament (TCL)

In agreement with Boss and Hintermann (2002) the tibiocalcaneal ligament (TCL) was a consistent band in the present study; however, it contradicts other reports of being present in 79% (Campbell et al., 2014), 94% Panchani et al. (2014) and 15% of specimens (Milner and Soames, 1998b). Panchani et al. (2014) stated that the TCL occurred bilaterally in 96.8% of specimens, while

Milner and Soames (1998b) report that it was always unilateral. These inconsistencies could be due to different names given to the deltoid bands, for example Milner and Soames (1998b) with respect to the TCL. Considering descriptions from other studies concerning the attachment of the TCL it has been suggested that it may be equivalent to the TSL or be even be referred to as the TSL (Milner and Soames, 1998b).

5.5.3.1 Proximal and Distal Attachments of the Tibiocalcaneal Ligament (TCL)

Panchani et al. (2014) considered that the TCL originated proximally from the medial malleolus, while Sarrafian (1993a) and Pankovich and Shivaram (1979a) observed the TCL proximal attachment to be from the medial surface of the anterior colliculus. In the current study it was confirmed to arise from the anterior colliculus, but only in 32.85% of specimens. The majority of specimens (56.9%) had a proximal attachment to the medial malleolus superior to the edge of the intercollicular groove (MMSIG), as well as to the medial surface of the anterior colliculus. Other proximal attachment sites were to the MMSIG and to the medial surfaces of the anterior and posterior colliculi (5.2%). Additionally, in two specimens (3.4%) the TCL attached only to the MMSIG; furthermore, one specimen (1.7%) had an attachment to MMSIG and medial surface and posterior edge of the anterior colliculus. The distance between the TCL proximal attachment to the medial surface of the medial malleolus and edge of the intercollicular groove was 3.59 ± 1.4 mm, less than the 6 mm of Campbell et al. (2014); Campbell et al. (2014) used frozen specimens and measured the distance between the TCL proximal attachment and the centre of the intercollicular groove inferiorly, while in the present study the distance was taken between a vertical line between the proximal TCL attachment and the edge of the intercollicular groove.

The current study observed that the TCL distal attachment was highly variable, including the calcaneus medial surface, sustentaculum tali, medial talar surface, spring ligament and talar posteromedial tubercle. However, the most common four sites of TCL distal attachment were to the spring ligament and sustentaculum tali (36.12%), sustentaculum tali only (18.97%), sustentaculum tali and talar posteromedial tubercle (27.59%) and to the sustentaculum tali, medial talar surface and posteromedial tubercle (10.34%). Previous investigations have also reported variations in the distal attachments of the TCL, the most common being to the sustentaculum tali (Campbell et al., 2014; Panchani et al., 2014; Palastanga et al., 2006; Milner and Soames, 1998b; Sarrafian, 1993a; Pankovich and Shivaram, 1979a). An attachment to the spring ligament was only reported by Sarrafian (1993a): other attachment sites, such as the talar and calcaneal medial surfaces have not been previously reported. Moreover, variation in the site of attachment to the sustentaculum tali has also been reported, being to the medial aspect of the sustentaculum tali (Milner and Soames, 1998b; Sarrafian, 1993a; Pankovich and Shivaram, 1979a), posterior (Campbell et al., 2014), superior (Panchani et al., 2014) or to the whole of the sustentaculum tali (Palastanga et al., 2006); Panchani et al. (2014) used formalin embalmed specimens while Pankovich and Shivaram (1979a) used both formalin and frozen specimens, however Milner and Soames (1998b) did not mention the type of embalming of their examined specimens. In the current study, when the TCL attached distally to the sustentaculum tali, it inserted into its superior and posterior (51.9%), posterior (18.5%), superior (14.8%), superior, posterior and medial (7.40%), posterior and medial (3.7%) and anterior, superior and posterior (3.7%) aspects. The TCL attachment to the sustentaculum tali appears to be controversial; however, the current study highlighted the exact site of attachment after a careful dissection and tracing of the ligament fibres to different parts of the sustentaculum tali, thus partly agreeing with previous studies. However, these sites were variable and not fixed to one site as reported previously. In addition, the TCL attached to the anterior (63.6%), anterior superior (31.85) and superior (4.5%) aspects of the talar posteromedial tubercle. The current study therefore provides exact distal attachment sites for the TCL in relation to the talar posteromedial tubercle and the sustentaculum tali.

5.5.3.2 Tibiocalcaneal Ligament (TCL) Dimensions

In the current study, TCL length with the ankle in neutral was 29.48 ± 4.36 mm, which is close to that reported by Campbell et al. (2014) (28.8 mm) and Ozeki et al. (2002) (27.7 ± 3.76 mm). However, TCL length is longer than in many studies: 25.6 ± 4.5 mm (Boss and Hintermann, 2002), 18 ± 7.7 mm (Milner and Soames, 1998a), 22.1 ± 3.5 mm (Luo et al., 1997) and 20 - 30 mm (Sarrafian, 1993a). This can probably be explained by the methodology used by Boss and Hintermann (2002) and Milner and Soames (1998a), in which TCL length was measured from insertion site to insertion site (free length) and therefore did not consider that part of the ligament attaching to bone. In addition, the observations of Boss and Hintermann (2002) and Luo et al. (1997) may be due to their small sample size (n = 12 and 11 respectively) compared to the current study (n = 48); therefore, these studies' findings may not be comparable. In the present study, TCL length was significantly greater in males (32.45 ± 4.11 mm) compared to females (27.54 ± 3.34 mm); again this may be due to the larger foot size in males. Further support for this is that TCL length was positively correlated with both foot length and 1st metatarsal length. There was also a positive correlation between TCL length and its mid width, which may be related to the TCL requiring a wider ligament at its mid-point for longer ligaments.

The proximal, middle and distal width of the TCL were 5.06 ± 1.8 mm, 5.21 ± 1.64 mm and 8.3 ± 3.03 mm respectively, less than Milner and Soames (1998a) who reported width as 9.5 ± 3.9 mm (proximal), 12 ± 5.8 mm (middle) and 22 ± 14.3 mm (distal). It is also less than Sarrafian (1993a), who reported proximal and distal width as 10 mm and 15 mm respectively. Although the latter two studies observed greater widths all studies agree that distal width is greater than proximal width. There is no obvious explanation for this inconsistency, but one possibility is that other parts of the deltoid ligament could have been included in the measurement, especially where there is no agreement on its different parts. The current study recommends further investigation of TCL width with a clear methodology, as well as defining the boundaries of the TCL as in the current study.

The current study showed that distal TCL width was significantly wider than both proximal and middle width due to its wide distal insertion (5.92 ± 3.14 mm) to the sustentaculum tali. TCL thickness was 0.96 ± 0.91 mm, less than previous reports which measured thickness directly: 2.8 ± 0.6 mm (Butler and Walsh, 2004), 1.8 ± 1.5 mm (Boss and Hintermann, 2002) and 2 – 3 mm

(Sarrafian, 1993a). The difference might be explained by the osteoligamentous preparations as well as the small sample sizes in Butler and Walsh (2004) (n = 8) and Boss and Hintermann (2002) (n = 12) compared to the present study (n =.49). It is interesting to note that these latter findings were greater than the thickness (1.2 mm) reported by Mengiardi et al. (2007) from MRI.

5.5.3.3 Tibiocalcaneal (TCL) Bony Attachment Lengths

No previous studies have reported the proximal and distal bony attachment lengths of the TCL: Campbell et al. (2014) and Boss and Hintermann (2002) both measured the proximal and distal footprint areas. There are significant differences in these reported areas with those of Campbell et al. (2014) (proximal and distal areas 29.4 mm^2 and 52.1 mm^2) being significantly larger than those of Boss and Hintermann (2002) (proximal area 17.1 ± 9.4 mm^2, distal area 19.8 ± 10.9 mm^2). This difference is confusing and appears to have no obvious cause; one possibility is that determination of the different parts of deltoid may have influenced the dimensions of Campbell et al. (2014), who found that the TCL was present in only 79%, while the TSL was always observed by Boss and Hintermann (2002) who reported that both the TCL and TSL were constant bands.

The current study found that the bony attachment lengths of the TCL were easy to define and determine. TCL bony attachment lengths were 18.15% of the total length proximally and 19.76% when it blended with spring ligament and its connecting fibres and attached distally to the sustentaculum tali: 62.09% of the total length had no bony attachment. The current study observed that TCL free length was 17 ± 4.75 mm, which might explain the difference with the reported length of Milner and Soames (1998a) (18 ± 7.7 mm), which was similar to the NBA (free length) in the current study. Nevertheless, there remains the difference with the free length of Boss and Hintermann (2002) (25.6 ± 4.5 mm), possibly because they had a smaller sample size (n = 12) compared to the current study (n = 31).

5.5.3.4 Relation to other Ligament and Bands

In the current study the relationship between the different parts of the deltoid ligament, as well as the continuity between the different bands, were investigated to provide precise detailed information to help in understanding the morphology and function of the deltoid ligamentous complex. The TCL was fully continuous with the STTL in 58.5% of specimens, while in the reminder it was partly continuous with the STTL: it separated from the STLL proximally 9.95 ± 3.11 mm distal to the TCL origin and distally 7.97 ± 3.85 mm proximal to the TCL insertion. The TCL was clearly separated from the deep layer of the deltoid. The fibrous tissue filling the gap between the talar posteromedial tubercle and sustentaculum tali were continuous with both the TCL and STTL, and may have a role in stabilising the talus and calcaneus medially. These observations of fibrous tissues have not been previously reported and it may aid in understanding of the function of the superficial layer of the deltoid ligament. In addition, minor fasciculation of the TCL was observed in the current study.. However, such fasciculation, which was small and could be easily missed, was not considered as true fasciculation into multiple bands and was not recorded as such. In the current study independent bands were considered when there was clear separation or different proximal and distal attachment sites, as well as different orientations. In addition, the observed fasciculation might be due to dehydration of the fibres or the effects of the formalin embalming; Brenner (2014) stated that formaldehyde based embalming solution causes tissue dehydration that deteriorates with time. Therefore, in the current study specimens were looked after by keeping them moist, spraying with formalin based solution, wrapping in cloths and keeping inside sealed plastic bags to minimise air exposure.

5.5.4 Superficial Posterior Tibiotalar Ligament (STTL)

The existence of the superficial tibiotalar ligament (STTL) is controversial. In the current study it was observed in 92.2% of specimens, which is similar to the 97% reported by Panchani et al. (2014). However, it is greater than that reported by Campbell et al. (2014) (79%), Boss and Hintermann (2002) (75%) and Milner and Soames (1998b) (37.5%). Such differences might be clarified by three explanations: the first of which is due to the different criteria for determining the different parts of deltoid as discussed earlier; the second is that the methodology and dissection may affect the STTL existence as it could be missed or lost during dissection; and finally sample size in Campbell et al. (2014) (n = 14) and Boss and Hintermann (2002) (n = 12) compared to that in the current study (n = 68). In addition, in the current study the STTL was bilateral in 94% of specimens, agreeing with Panchani et al. (2014) (93.75%), but not Milner and Soames (1998b) (36.36%); however, Milner and Soames only observed the STTL in 37.5% of specimens.The present study's observations showed that foot side and gender had no association with the existence of the STTL.

In the current study the anterior part of the STTL was partly covered by some fibres of the TCL in 14% of specimens. Pankovich and Shivaram (1979a) reported the relationship between the TCL and STTL and how they could be differentiated by their distal attachments, which agree with the findings of the current study.

5.5.4.1 Proximal and Distal Attachments of the Superficial Tibiotalar Ligament (STTL)

There is disagreement in the literature on the exact site of the proximal STTL attachment, including: the medial surface of the anterior colliculus (Cromeens et al., 2015), the medial side of the posterior colliculus (Milner and Soames, 1998b), the posteromedial surface of the tibial medial malleolus (Panchani et al., 2014), and the medial surface of the posterior segment of the anterior colliculus and partly from the posterior colliculus (Pankovich and Shivaram, 1979a). In the current study the STTL originated from the medial malleolus but with different sites of attachment with the most common being to superior to the edge of the intercollicular groove (IG), observed in 70% of specimens. Other proximal attachments include: anterior to the posterior colliculus, the medial surface of the anterior colliculus and anterior part of the posterior colliculus. These differences may be related to the extent of the dissection that was undertaken to reveal the proximal attachment: furthermore, differences might be due to the small sample sizes (Cromeens et al., 2015: n = 9); Pankovich and Shivaram, 1979a; n = 16) compared to the current study (n = 50). In the present study, the distance between the STTL proximal attachment and the edge of the intercollicular groove was 2.23 ± 1.43 mm, while Campbell et al. (2014) reported the distance between STTL origin and the centre of the intercollicular groove as 3.5 mm. In the present study the distance between the STTL origin and the edge of the intercollicular groove was greater in specimens with greater foot and 1st metatarsal lengths.

Disagreement regarding the distal attachment of the STTL has also been reported, including to: the talus with 66.66% inserting to the posterosuperior aspect of the sustentaculum tali (Cromeens et al., 2015), the posteroinferior aspect of the talar medial surface and 10.4 mm anterosuperior to the posteromedial tubercle (Campbell et al., 2014), the superoposterior surface of the talus (Panchani et al., 2014), the sustentaculum tali and posteromedial tubercle (Milner and Soames, 1998b) and the anterior part of the posteromedial tubercle (Pankovich and Shivaram, 1979a). The current study observed the STTL to have variable distal insertions into the talar medial surface (95.85%), posteromedial tubercle (89.3%) and sustentaculum tali (17%). The distal STTL attachments include the talar medial surface in addition to the anterior and superior aspects of the posteromedial tubercle (46.8%), the superior aspect of posteromedial tubercle (21.3%), the anterosuperior to the posteromedial tubercle (8.5%) and the anterior and superior aspects of the posteromedial tubercle as well as the posterosuperior aspect of the sustentaculum tali (8.5%). The current study does not agree with the previous investigations. Discrepancies in defining the precise distal STTL attachment may be due to the dissection protocol used in revealing the end of the attachment, or may be due to the smaller sample sizes in the studies by Cromeens et al. (2015) (n = 9), Campbell et al. (2014) (n = 14) and Pankovich and Shivaram (1979a) (n = 16) compared to the current study (n = 47). In addition, an attachment to the sustentaculum tali was seen in 17% of specimens, even though the distal STTL fibres projected and blended with the distal TCL fibres in order to fill the gap between the talar posteromedial tubercle and sustentaculum tali.

5.5.4.2 Superficial Tibiotalar Ligament (STTL) Dimensions

Panchani et al. (2014) pointed out that there is variation in the reported length of the STTL. In the current study it was measured in neutral, being 23.08 ± 3.75 mm, close to the previously reported ranges of 20 ± 4.3 mm (Boss and Hintermann, 2002), and 21 mm (Campbell et al., 2014); however, it is at variance with the 14 ± 3.7 mm of Milner and Soames (1998a). Milner and Soames (1998a) indicated that length was measured between insertion sites (free length): this would explain the shorter length. The present study found a significant difference between genders, with STTL length being significantly greater in males (25.63 ± 3.85 mm) compared to females (21.46 ± 2.66 mm), probably due to the larger feet in males, which is supported by the finding of STTL length being positively correlated with both foot length and 1st metatarsal length.

Milner and Soames (1998a) reported STTL width as 8 ± 2.8 mm, which is significantly greater than the proximal, middle and distal widths in the current study (5.23 ± 4.41 mm, 5.06 ± 1.45 mm and 5.66 ± 2.06 mm respectively).

There is no obvious cause for this difference, but it could partly be due to the smaller sample size in Milner and Soames (1998a) (n = 15) compared to the present study (n = 49). In the current study the distal STTL width was significantly greater compared to proximal and middle widths: this is probably due to the wide and variable insertion sites of the ligament. Furthermore, proximal width was negatively correlated with age, which suggests that ageing affects the proximal width due to degenerative changes.

There is only one previous report of STTL thickness as 1.2 ± 0.5 mm (Boss and Hintermann, 2002). This is slightly greater than that observed in the present study (0.89 ± 0.92 mm). The lengths and dimensions reported by Cromeens et al. (2015) appear to include part of the TCL (according to this study's definition of the deltoid bands) in their measurements; therefore, comparison with this is not directly possible.

5.5.4.3 Superficial Tibiotalar Ligament (STTL) Bony Attachment Lengths

In reviewing the literature, there are no previous reports of the proximal and distal bony attachment lengths; however, both Campbell et al. (2014) and Boss and Hintermann (2002) measured the proximal attachment area, being 31.7 mm^2 and 13.8 ± 5.5 mm^2 respectively. It is clear that these studies disagree, possibly because of different criteria used for defining or considering the different parts of the deltoid complex. Furthermore, Cromeens et al. (2015) and Campbell et al. (2014) disagree on the STTL talar attachment area, being 26.39 ± 17.42 mm^2 and 38.3 mm^2 respectively. Calculation of the attachment or footprint area was not methodologically clarified in the above studies; therefore, their footprint area may not be comparable. As stated earlier, knowledge of the bony attachment lengths, as well as the distal width, provides an easy and practical way of determining how much of a ligament attaches to a specific bone: this information may have clinical, surgical and/or biomechanical applications.

The current study is the first to report the proximal and distal bony attachment lengths of the STTL, these being 4.28 ± 3.73 mm (proximal) and 3.38 ± 2.29 mm (distal) comprising 17.52% and 13.84% of the total STTL length respectively. The free length, or no bony attachment length, (16.77 ± 4.89 mm) comprised 68.65% of the STTL total length. The free length observed in the current study is closer to that reported by Milner and Soames (1998a) (14 ± 3.7 mm). In addition, the current study observed that free length was greater in males (18.5 ± 5.12 mm) compared to females (15.29 ± 4.27 mm), again probably attributable to the larger foot size and STTL length in males. This is reinforced by the positive correlation observed between the STTL free length (NBA) and both 1st metatarsal length and STTL length.

5.6 Deep Layer of the Medial Collateral Ligaments (Deltoid)

The anterior (ATTL) and posterior (PTTL) tibiotalar ligaments were both components of the deep layer of the deltoid complex, agreeing with Campbell et al. (2014), Wenny et al. (2014) Pankovich and Shivaram (1979a) and Palastanga et al. (2006). In addition, the ATTL and PTTL originated proximally from the medial malleolus attaching to the anterior colliculus and intercollicular groove and inserted distally into the medial surface of the talus in agreement with Pankovich and Shivaram (1979a). However, Sepúlveda et al. (2012) reported that the morphology of the deep layer was consistent with no variations or differentiation between its anterior and posterior parts. This contradicts the current study’s findings as the deep layer of the deltoid was variable, with the anterior part originating from the anterior colliculus and the posterior part filling the intercollicular groove between the anterior and posterior colliculi.

5.6.1 Deep Posterior Tibiotalar Ligament (PTTL)

The deep posterior tibiotalar ligament (PTTL) was a large and consistent part of the deep layer of the deltoid ligament, thus agreeing with many previous studies (Cromeens et al., 2015; Campbell et al., 2014; Panchani et al., 2014; Boss and Hintermann, 2002). In the current study, the PTTL had wide proximal and distal attachments, as well as a variable morphology.

5.6.1.1 Band Number of the Deep Posterior Tibiotalar Ligament (PTTL)

Fasciculation of the PTTL has not being previously investigated, although Milner and Soames (1998b) did observe PTTL fasciculation but with no evidence for multiple bands. In the current study, different forms of the PTTL were observed. Following careful dissection multiple bands were seen, with the different bands having different distal attachments and exhibited clear separation from each other at various levels. The two (45.2%) and three (45.2%) band forms were the most common, with one (8.1%) and four (1.61%) band forms also being observed; the one band form was always unilateral, while the two common forms (two and three band) were seen bilaterally in about half of the specimens. In addition, all one band forms of the ligament were seen in female specimens; this may be due to smaller feet in females. No previous studies have reported different PTTL bands, with previous studies only giving brief details of the deep layer. In addition, the superficial part of the ligament covered most parts of the deep layer: inappropriate reflection of this layer during dissection may result in missing the fasciculation. All specimens with multiple bands were carefully dissected to preserve as many ligament fibres as possible; fat and other tissues, such as capsular fibres, were cleared and photographs taken to document evidence of PTTL fasciculation.

In the present study, isolated subtalar inversion PROM was significantly smaller in the three band form (11° ± 4°) compared to the one (13º ± 5°) and two (12° ± 4°) band PTTL forms, suggesting that the three band form may have a greater restricting effect on inversion compared to other PTTL forms. In the current study, each part or band of the PTTL was referred to separately: anterior (APTTL), posterior (PPTTL) and middle (MPTTL) band of the PTTL according to its position. The APTTL was the most anterior band and was also referred to as the one band form.

5.6.1.2 Ligaments Superficial to the Deep Posterior Tibiotalar Ligament (PTTL)

Panchani et al. (2014) reported that the PTTL was covered superficially by the STTL, while Campbell et al. (2014) stated that both the TCL and STTL covered the PTTL. In the current study superficial ligaments covering the PTTL included the TSL, TCL and STTL. In addition, variations in covering styles were observed allowing a detailed morphological relationship between the superficial layer and PTTL to be established. The APTTL was mainly covered by the TCL and STTL (40.9%), the TCL (20.5%), the TSL and TCL (13.6%), the STTL (9.1%) and the TSL, TSL, TCL and STTL (4.5%). In addition, the MPTTL was deep to the STTL (54.5%), the TCL and STTL (22.7%), part of the STTL (9.1%), the TSL, TCL and STTL (9.1%) and the TSL, TCL, STTL and APTTL (4.5%). Moreover, the PPTTL was partly covered by STTL (54.5%), or had no covering at all (29.5%) or showed complete covering by the STTL (4.5%). The current study has therefore provided exact anatomical relationships between the superficial and deep components of the deltoid ligament.

5.6.1.3 Proximal Attachment of the Deep Posterior Tibiotalar Ligament (PTTL)

The posterior tibiotalar ligament (PTTL) was observed to attach proximally to the medial malleolus filling the whole of the intercollicular groove between the posterior part of the anterior colliculus and the anterior part of the posterior colliculus, thereby agreeing with Cromeens et al. (2015) and Milner and Soames (1998b). However, no earlier studies reported the proximal attachment of each PTTL band.

5.6.1.4 Distal Attachment of the Deep Posterior Tibiotalar Ligament (PTTL)

In reviewing the literature, the posterior tibiotalar ligament (PTTL) inserts distally to the medial surface of the talus (Cromeens et al., 2015; Drake et al., 2010a;

Palastanga et al., 2006), as well as being inferior to the facies malleolaris medialis (medial malleolar articular surface) (Cromeens et al., 2015): this was confirmed in the present study. However, a number of reports in textbooks have stated that the PTTL had a distal attachment to the posteromedial tubercle of the talus (Drake et al., 2010a; Standring, 2008; Palastanga et al., 2006; Milner and Soames, 1998b; Pankovich and Shivaram, 1979a): in the current study this was observed in only 2 specimens in which either the APTTL in the one band form or the PPTTL in the two band form attached to the anterior part of the talar posteromedial tubercle. In addition, no previous studies have reported the PTTL distal attachment of the different bands, even though separations of the different bands as well as clear and different levels of attachment have been observed. Many students and clinicians use anatomy textbooks to find information on the morphology of the ankle collateral ligaments; therefore, the descriptions of the morphology of the current study was compared to these textbooks.

The APTTL inserted distally to the medial surface of the talus, commonly (96.4%) anterosuperior to the posteromedial tubercle of the talus. One specimen of the one band form had a distal attachment anterosuperior to the posteromedial tubercle, as well as to the anterior border of the posteromedial tubercle; however, another specimen attached to the talar medial surface posterosuperior to the posteromedial tubercle. Significant differences were observed in the APTTL distal attachment, being anterosuperior to the talar posteromedial tubercle in 60% of the one band form, while this was always the case in the two, three and four band forms.

In the current study, the PPTTL attached distally anterosuperior (51.9%) or posterosuperior (46.2%) to the posteromedial tubercle of the talus. In one specimen in the two band form it attached anterosuperior to the posteromedial tubercle, but also had fibres attaching to the anterior part of the posteromedial tubercle. The MPTTL inserted distally to the talar medial surface either anterosuperior (95.8%) or posterosuperior (4.2%) to the posteromedial tubercle. Defining either the attachment as anterosuperior or posterosuperior was verified by measuring the angle between the middle point of the distal attachment of each band and the posteromedial tubercle of the talus. For angles less than 90° the distal attachment was considered to be anterosuperior and for angles greater than 90° it was considered posterosuperior to the posteromedial tubercle of the talus.

One of the objectives of the current study was to precisely define the distal PTTL attachment; therefore, the distance and angle between the mid point of the distal attachment of each PTTL band and the posteromedial tubercle of the talus were measured. This is the first study to report the distal insertions of the different PTTL bands. The distance and angle between the distal attachment of the APTTL and the posteromedial tubercle were 10.19 ± 3.37 mm and 41° ± 18° respectively, with the distance being significantly greater in males (11.41 ± 3.1 mm) compared to females (9.44 ± 3.36 mm) which may be a reflection of the larger foot size in males. This was supported by the positive correlation between this distance and both foot length and 1st metatarsal length. In addition, the distance was different in relation to the number of PTTL bands: in the one band form it was closer to the posteromedial tubercle of the talus (5.55 ± 0.77 mm) compared to the two (9.94 ± 3.36 mm), three (11.5 ± 3.02 mm) and four (9.83 mm) band forms. In addition, the angle in the one band form (65° ± 33°) was greater than that in the two (45° ± 14°), three (33° ± 13°) and four (22°)

band forms, indicating that the distal attachment of a single band PTTL is more posterior than in other forms. In addition, it suggests that the morphology of the distal insertion of the anterior band becomes more posterior as the band number increases. It was also observed that the distance between the APTTL distal attachment and the talar posteromedial tubercle and the distal width were negatively correlated, probably due to the greater distal width between the midpoint of the distal attachment and the posteromedial tubercle. However, distal width was positively correlated with the angle between the APTTL distal attachment and the posteromedial tubercle. This could be explained as a greater distal width moves the midpoint of the distal insertion more posteriorly causing the angle to increase. In addition, the distance was negatively correlated with the angle, which again might be due to moving the midpoint of the distal attachment anteriorly leading to a reduction in the angle between it and the posteromedial tubercle. This might help in understanding the growth and development of the ligament.

The distance and angle between the MPTTL distal attachment and the posteromedial tubercle were 8.39 ± 1.88 mm and 56° ± 20° respectively, with the distance again being significantly greater in males (9.23 ± 1.49 mm) compared to females (7.54 ± 1.91 mm). In addition, the angle was significantly greater on the left (66° ± 18°) compared to the right (43° ± 14°): there is no obvious reason for such a difference. Furthermore, there was a positive correlation between this distance and foot length, which could be explained by larger bones in larger feet increasing the distance between the posteromedial tubercle and MPTTL distal attachment. In addition, the angle was positively correlated with the MPTTL distal width, suggesting that a wider ligament distally would lead to the mid distal attachment to move posteriorly creating a larger angle between the distal attachment of the MPTTL and the posteromedial tubercle. The distance and angle between the PPTTL distal attachment and the posteromedial tubercle were 7.29 ± 2.34 mm and 87° ± 19° respectively. Surprisingly, age was negatively correlated with the distance between the distal attachment of the APTTL, MPTTL and PTTL and the posteromedial tubercle of the talus. This correlation is interesting and poses questions such as ‘What is the effect of aging on attachment of the ligaments?’ and ‘Does ossification due to degenerative changes lead to changes in the morphology of the distal PTTL attachment leading to it being closer to the posteromedial tubercle?’. These questions may lead to further investigations using a larger number of specimens from different age groups (in the current study the age range was between 62 to 98 years) to determine PTTL morphology in relation to the bony landmark (posteromedial tubercle) used in the current study. Histological investigations of the talus, as well as of the ligament in different age groups may help to answer these questions. One final question which needs to be addressed is whether aging causes any change to the biomechanics of the ligament or the way in which it functions.

5.6.1.5 Posterior Tibiotalar Ligament (PTTL) Dimensions

In reviewing the literature variable PTTL lengths ranging between 9.5 mm and 26.68 mm have been reported. However, some studies report lengths between 9.5 mm and 13.44 mm (Campbell et al., 2014; Wenny et al., 2014; Milner and Soames, 1998a; Luo et al., 1997; Siegler et al., 1988), while others report lengths between 16.8 mm and 26.68 mm (Cromeens et al., 2015; Wenny et al., 2014; Mkandawire et al., 2005; Boss and Hintermann, 2002). However, no previous studies have determined the length of individual PTTL bands, which may be expected as they did not report the PTTL as a multiband structure. In the current study PTTL band lengths were 14.89 ± 4.02 mm (APTTL), 15.8 ± 3.8 mm (MPTTL) and 15.2 ± 3.92 mm (PPTTL), which are close to the length (16.8 ± 5.6 mm) reported by Boss and Hintermann (2002). However, they measured length from insertion to insertion, suggesting that they did not include the whole bony attachment lengths. The discrepancies in reported ligament length, including those in the current study, need to be investigated further as the differences are large. There are three possible explanations for the differences in PTTL length. Firstly, the STTL was included in the measurement as it can be confused with the insertion of the PTTL, as both have an attachment to the talar medial surface: this would explain the greater lengths reported. Secondly, most studies had small sample sizes between 6 and 20 (Cromeens et al., 2015; Campbell et al., 2014; Wenny et al., 2014; Mkandawire et al., 2005; Boss and Hintermann, 2002; Luo et al., 1997; Siegler et al., 1988) compared to the current study, which measured length in 51 specimens. Finally, the nature of the specimens might have an effect on ligament length, for example Cromeens et al. (2015), Campbell et al. (2014), Boss and Hintermann (2002) and Siegler et al. (1988) used frozen specimens, Mkandawire et al. (2005) used fresh unembalmed specimens, while Milner and Soames (1998a) and Luo et al. (1997) did not state whether the specimens used were either frozen or embalmed. A standardised method of measuring the PTTL should be introduced to enable better comparisons of its length, which may have clinical and biomechanical applications. The methodology used in the present study is clearly outlined in the methods section of this thesis: it is considered that the measurements were reliable considering the technique employed and the sample size used.

In the present study, APTTL and PPTTL length were significantly greater in males (17.43 ± 3.7 mm and 17.06 ± 4 mm) compared to females (13.11 ± 3.2 mm and 13.71 ± 3.19 mm), which is not surprising given the positive correlation between APTTL length and foot length and 1st metatarsal length and between PPTTL length and 1st metatarsal length. Furthermore, APTTL and PPTTL length were not different in the one, two or three band forms of the PTTL, suggesting that being single or multi banded does not influence its length: this is supported by the positive correlation between PPTTL length and both APTTL and MPTTL lengths.

The APTTL proximal, middle and distal width were 3.94 ± 2.13 mm, 3.98 ± 2.15 mm and 4.83 ± 2.61 mm respectively; the middle and distal widths weresignificantly wider in the one band form (8.96 mm - 11.38 mm) compared to the two (3.77 mm – 4.64 mm), three (3.2 mm – 3.92 mm) and four (1.74 mm – 2.02 mm) band PTTL forms, suggesting that the one band PTTL compensates for the additional bands by providing an appropriate functional distal attachment. In addition, APTTL distal width was positively correlated with APTTL distal bony attachment length, suggesting that a wider insertion of the ligament may require a longer DBA to enable the ligament to perform its functional role of stabilising the ankle. In addition, APTTL proximal, middle and distal widths were positively correlated with APTTL length, suggesting that a wider ligament is needed for a longer ligament to preserve its functional and mechanical properties.

MPTTL widths were 3.5 ± 1.48 mm (proximal), 2.84 ± 1.06 mm (middle) and 3.33 ± 0.99 mm (distal), with MPTTL length being positively correlated with proximal and middle width. The proximal, middle and distal width of the PPTTL were 4.92 ± 1.85 mm, 4.55 ± 1.52 mm and 5.95 ± 2.04 respectively. PPTTL mid and distal widths were significantly wider in the two band form (5.25 ± 1.39 mm and 6.82 ± 1.97 mm) compared to the three band form (3.94 ± 1.39 mm and 5 ± 1.74 mm), perhaps in an attempt to compensate for the missing middle band.

In the present study, the total width of the PTTL irrespective of band number was determined to provide a width value for the whole ligament, as well as to be able to compare the width with previous studies: the total width was 10.08 ± 2.75 mm (proximal), 9.43 ± 1.92 mm (middle) and 11.87 ± 2.45 mm (distal). These values are close to the PTTL width of 10.4 mm by Panchani et al. (2014) and the 9.94 ± 2.97 mm and 8.31 ± 1.9 mm of Wenny et al. (2014). However it differs from others: 14.4 ± 1.8 mm (Cromeens et al., 2015) and 17 ± 7.1 mm (Milner and Soames, 1998a). It is difficult to explain these greater width values, but one possible explanation could be due to the dissection technique used in exposing the PTTL and defining its borders from other parts of the deltoid ligament. Additionally, Cromeens et al.'s (2015) results may not be accurate due to their small sample size (n = 9) compared to the current study (n = 51 – 58). In the current study, gender was a factor in the total middle width of the PTTL as males (10.22 ± 1.61 mm) had a significantly greater total middle width compared to females (8.88 ± 1.96 mm): this is probably due to the larger foot size in males. This was confirmed by the positive correlation between the PTTL total middle width and both foot length and 1st metatarsal length.

The difference in the mid total width compared to the total proximal and total distal widths, as well as the significant difference between the total proximal and total distal widths, showed that total distal width was the greatest, while total proximal width was significantly wider than total mid width. This is supported by the positive correlations between all total PTTL widths. The total proximal width was significantly different in relation to the band number of the PTTL; the three band form had the widest total proximal width compared to the one, and two band forms. However, the total mid and distal widths did not differ in the different band forms suggesting that the one, two, three or four band forms do not change their total middle and distal widths. Moreover, the total middle and distal widths of the PTTL were negatively correlated with the age, suggesting that the middle and distal widths get smaller with aging causing loosening of fibrous tissue from the ligament due to degenerative changes. Figure 5.1 summarizes the observed length and width of the PTTL in the different band forms in the current study compared to the range of length reported in previous studies.

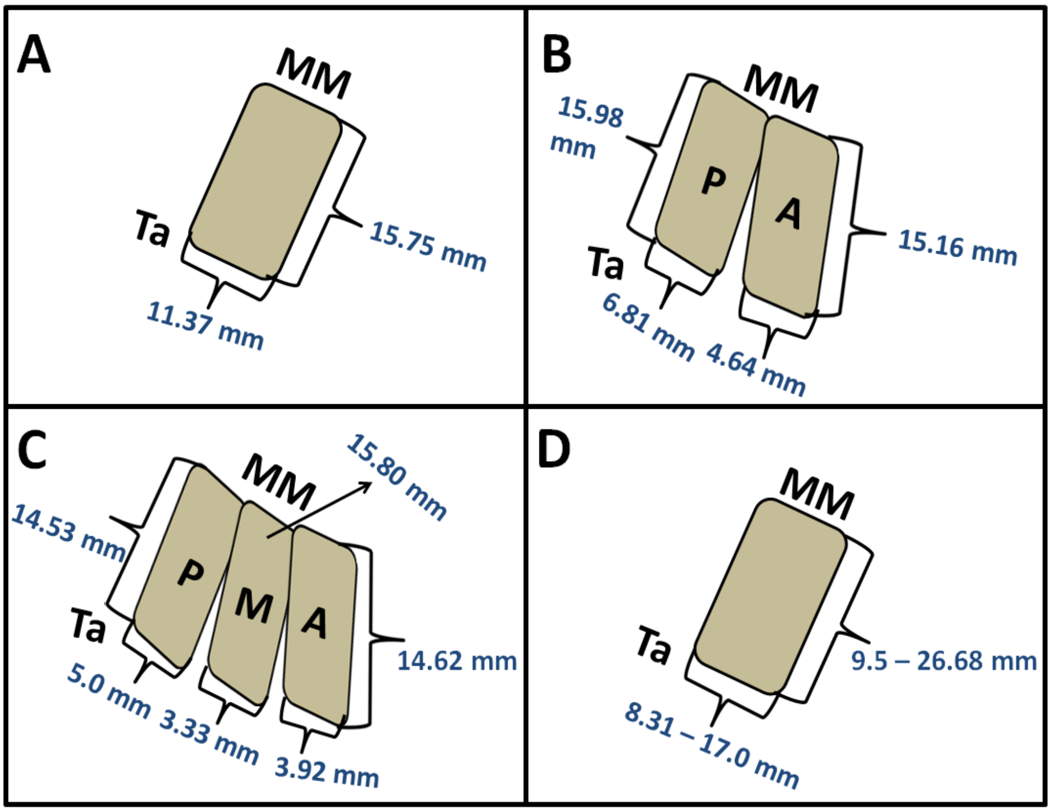

Figure 5.1 Length and width of the PTTL measured in the current study (A, B, C) being compared to the range that was reported in previous investigations (D): A, one band form; B, two band form; C, three band form; MM, medial malleolus; Ta, talus.

Cromeens et al. (2015) stated that measuring PTTL thickness was difficult due to the approximation and short distance between origin and insertion. However, it was possible to measure thickness in the present study, particularly at the middle point of the ligament with the ankle in full dorsiflexion, thus allowing full elongation of the ligament increasing the distance between the origin and insertion. In the current study thickness was 1.46 ± 0.76 mm (APTTL), 0.85 ± 0.39 mm (MPTTL) and 1.53 ± 0.61 mm (PPTTL); however, these values differ from previous studies. Boss and Hintermann (2002) reported a thickness (1.6 ± 0.6 mm) close to that of this study; however, Panchani et al. (2014) reported a smaller value (0.6 mm), while Butler and Walsh (2004) reported it as 2.9 ± 1.1 mm, much greater than all previous studies and the current study. Klein (1994) reported that the PTTL, observed from MRI, was the thickest ligament of all deltoid components. Mengiardi et al. (2007) also measured PTTL thickness from MRI scans and found it to be 8.2 mm, which is significantly greater than studies which directly measured the PTTL. It has to be noted that MRI always reports greater thicknesses, possibly caused by measuring the whole ligament without loss of any fibres that may occur during dissection: MRI slice size may affect the reported measurement. Therefore, it is important in studying the ankle (or any other) ligaments to differentiate between direct physical measurement and measurements obtained from MRI images.

In the present study, PPTTL thickness was greater in males (1.72 ± 0.71 mm) compared to females (1.36 ± 0.46 mm); however, there was no correlation between the PPTTL thickness and foot length or 1st metatarsal length. Furthermore, APTTL and PPTTL thickness were not different in the two or three band PTTL forms. In addition, the positive correlations between PPTTL thickness and both the proximal and middle widths suggest that a wider PPTTL proximally or at its middle may require a thicker ligament in order to maintain the same mechanical properties in relation to its function.

5.6.1.6 Posterior Tibiotalar Ligament (PTTL) Bony Attachment Lengths

There are no reports in the literature of the proximal and distal bony attachment lengths of the PTTL. However, Boss and Hintermann (2002) gave the proximal and distal attachment areas as 24.3 ± 21.9 mm^2 and 38.8 ± 38.7 mm^2 respectively, while Cromeens et al. (2015) reported the proximal attachment area being 111.65 ± 27.42 mm^2, and Wenny et al. (2014) demonstrated that the

ATTL and PTTL had a combined attachment area of 101 ± 13 mm². Wenny et al. (2014) and Cromeens et al. (2015) also reported the distal attachment area as 98 ± 20 mm² and 140.89 ± 41.93 mm² respectively. It is clear that there is wide variation in the proximal and distal attachment areas of the PTTL that may lead to misunderstanding of the attachment of these ligaments. As the methodology of measuring these attachment areas was not clear, it is suggested that the proximal (PBA) and distal (DBA) bony attachment lengths as well as the proximal and distal widths provide an easier and more practical alternative in determining the proximal and distal attachments to bone, and how much of the ligament is directly attached to a specific bone. This information could be useful in clinical and biomechanical investigations of the attachment mode of any ligament.

The current study is the first to report the bony attachment lengths of the PTTL. The APTTL had a proximal and distal bony attachment length of 4.38 ± 1.81 mm and 3.32 ± 1.85 mm, comprising 27.9% and 21.15% of its total length leaving a free length (NBA) of 8.08 ± 2.55 mm, i.e. 51.46% of the total length. The APTTL NBA was greater in males (9.14 ± 3.19 mm) compared to females (7.24 ± 1.52 mm), perhaps not surprising given the positive correlation between APTTL NBA and both foot length and 1^{st} metatarsal length: both foot and1^{st} metatarsal length were significantly greater in males than females. In addition, there was a positive correlation between the APTTL distal bony attachment length (DBA) and APTTL distal width, suggesting that a wider APTTL insertion may require a longer bony attachment to provide the ligament with an opportunity to provide the appropriate stabilisation without being disrupted.

The MPTTL in the three band form had proximal (PBA) and distal (DBA) bony attachment lengths of 2.82 ± 1.31 mm 2.68 ± 1.68 mm and a no bony attachment length (NBA) of 10.70 ± 3.96 mm: these values comprised 17.4%, 16.53% and 66.01% of the total length respectively. A positive correlation between the MPTTL PBA and DBA suggests that a balance of proximal and distal attachment length is required to prevent the ligament from becoming disrupted during joint stabilisation.

The bony attachment lengths of the PPTTL were 3.25 ± 1.67 mm (PBA), 5.08 ± 2.53 mm (DBA) and 8.03 ± 2.38 (NBA), comprising 19.87%, 31.05% and 49.08% mm of the total length respectively. Males had a significantly greater PPTTL DBA (6.07 ± 2.64 mm) compared to females (4.22 ± 2.14 mm). There were positive correlations between PPTTL thickness and PPTTL NBA and PPTTL DBA, suggesting that thickness is important in maintaining ligament stability and its attachment to the talus: a longer NBA may resist deformation during stretching in ankle movements.

5.6.1.7 Four Bands of the PTTL and Other Relations

In the present study, one specimen was observed with a four band form of the PTTL having two middle bands: one superficial deep to the STTL and one deep covered by the superficial MPTTL. The lengths of the middle bands were 15.25 mm (superficial) and 9.84 mm (deep), while the middle width and thickness were 4.97 mm and 0.76 mm respectively (superficial) and 4.43 mm (deep). The superficial MPTTL originated proximally from the intercollicular groove and posterior aspect of the anterior colliculus, while the deep MPTTL had its proximal attachment superior to the edge of the intercollicular groove extending to the intercollicular groove. Both bands inserted distally into the medial surface of the talus inferior to the medial malleolar articular surface, as well as anterosuperior to the posteromedial tubercle of the talus.

The current study also investigated the relationship between the PTTL and ATTL, as well as the different bands of the PTTL, in order to provide a comprehensive understanding of the morphology of this main component of the deep layer of deltoid. The PTTL proximal attachment had a connection to that of the ATTL in 80% of specimens, with PTTL fibres leaving the ATTL 6.26 ± 2.54 mm distal to the PTTL origin, 68.75% of which had the PTTL origin 3.55 ± 2.04 mm proximally in the ATTL. The separation between the different bands of the PTTL did not consider the deep attachment to the intercollicular groove; however, it was considered when the band was viewed medially.

The two band form showed the APTTL origin joining the PPTTL origin separating 5.64 ± 3.04 mm distal to the APTTL origin; however, in 21.88% of specimens the APTTL was 1.31 ± 0.73 mm superior to the PPTTL origin. This can be explained by the shape of the intercollicular groove as it gives attachment to both bands. The two bands continued crossing inferiorly, being independent from each other until 2.42 ± 1.46 mm proximal to the APTTL insertion: this was observed in 94.2% of specimens, while in the reminder there was no connection at the insertion sites. Furthermore, in 18.75% of specimens the APTTL extended 0.91 ± 0.54 mm inferior to the PPTTL insertion.

The three band form showed the APTTL joining the MPTTL proximally in 82.35% of specimens separating 5.57 ± 2.37 mm distal to the APTTL origin;

however, in 14.29% of specimens the APTTL extended proximally 3.12 ± 3.03 mm to the MPTTL origin. In addition, the APTTL had a joint insertion with the MPTTL separating 3.74 ± 2.36 mm proximal to the APTTL origin. The MPTTL was separated in 6.67% of specimens, while in 86.66% of specimens it had a joint origin with the PPTTL separating 7.73 ± 3.19 mm distal to the MPTTL origin in 76.9% of these proximal attachments, the MPTTL origin was 2.13 ± 0.94 mm superior and free from the PPTTL origin. This could be due to the shape of the intercollicular groove, as well as the location of the MPTTL band. Distally in 88.89% of specimens the MPTTL had a joint insertion with the PPTTL that separated 2.71 ± 1.46 mm proximal to the MPTTL insertion: in one case the MPTTL extended 0.65 mm inferior to the PPTTL insertion.

5.6.2 Anterior Tibiotalar Ligament (ATTL)

The anterior tibiotalar ligament (ATTL) was part of the deep layer of the deltoid ligament in 96.7% of specimens, agreeing with Campbell et al. (2014), Panchani et al. (2014) and Klein (1994) who reported the existence of the ATTL in 93%, 86% and 84% of specimens respectively. However, there is disagreement with Cromeens et al. (2015) (66.7%), Boss and Hintermann (2002) (50%) and Milner and Soames (1998b) (10%). These differences might be due to different dissection techniques in preserving the band, as well as the smaller sample sizes in Cromeens et al. (2015) (n = 9) and Boss and Hintermann (2002) (n = 12); this may suggest that their results are less reliable than the findings of the current study. Another possibility is that some observers might have considered the ATTL as part of the TNL deep layer: in the current study the deep layer of the TNL was attached to the ATTL superficially covering it in many specimens.

5.6.2.1 Band Number of the Anterior Tibiotalar Ligament (ATTL)

No previous studies have reported the ATTL with more than one band: in the current study 70.7% of specimens had a single band, while in the reminder (29.3%) had two bands. The one band was commonly seen to be bilateral (70.6%), which was the typical form of the ATTL; the two band form was bilateral in 40% of specimens, with the two bands being two independent bands. This could have been missed in previous investigations be due to the dissection technique used. In the current study, the gender or the dominant side had no effect on the existence of the single or two band forms of the ATTL.

5.6.2.2 Ligaments Superficial to the Anterior Tibiotalar Ligament (ATTL)

Differences in ligaments covering the ATTL have been reported in the literature, being covered by the TNL and TSL (Campbell et al., 2014), the TNL and TCL (Drake et al., 2010a), or the TCL which may blend with it (Pankovich and Shivaram, 1979a). In the present study, there were also variations: it was covered by the TSL and TCL (29.4%), the TSL (26.5%) and the TNL, TSL and TCL (14.7%). The anterior band in the two band form (AATTL) was deep to the TNL and TSL (61.5%), the TSL (30.8%) and the TNL (7.7%), while the posterior band (PATTL) was deep to the TSL and TCL (63.6%), the TNL and TSL (18.2%), the TSL (9.1%) and the TCL (9.1%).

5.6.2.3 Proximal Attachment of the Anterior Tibiotalar Ligament (ATTL)

There is some disagreement and lack of detail concerning the exact site of the ATTL proximal attachment. Milner and Soames (1998b) and Pankovich and Shivaram (1979a) both reported the ATTL had an attachment to the intercollicular groove: this was not observed in the present study as the ATTL was mostly superficial to the PTTL and thus to the intercollicular groove. However, fibres that attached to the anterior aspect of the anterior colliculus spread into the intercollicular groove were considered as part of the PTTL. Campbell et al. (2014), Standring (2008) and Cromeens et al. (2015) stated that the ATTL attached proximally to the tip of the anterior colliculus: this was partly observed in the present study as the single ATTL had a typical proximal attachment to both the medial surface and tip of the anterior colliculus in 71.1% of specimens. Other common sites of attachment were to the medial surface of the anterior colliculus (21.1%), the typical origin plus the anterior surface of the anterior colliculus (2.6%), the typical origin plus the posterior surface of anterior colliculus (2.6%) or the medial surface of the anterior colliculus and posterior to the tip (2.6%). Furthermore, in the current study the AATTL had a typical origin in 46.7% of specimens, while in the reminder it was either to the medial surface of the anterior colliculus (46.7%) or the anterior surface of the anterior colliculus (6.7%). The PATTL had the typical origin in 13.3% of specimens, while it attached proximally to the medial surface of the anterior colliculus (80%) or the tip of the anterior colliculus only (6.7%).

5.6.2.4 Distal Attachment of the Anterior Tibiotalar Ligament (ATTL)

In the current study, the ATTL in both band forms inserted distally into the talar medial surface distal to the medial malleolar articular surface and anterosuperior to the posteromedial tubercle. The distal attachment has been variably reported by others: Panchani et al. (2014) stated the insertion as anterosuperior to the medial malleolus, while Campbell et al. (2014) observed it distal to the talar articular cartilage; while these descriptions are correct they do not give precise attachment sites. Both Wenny et al. (2014) and Palastanga et al. (2006) reported an attachment to the neck of the talus, while Pankovich and Shivaram (1979a) stated that the insertion is close to the neck of the talus. In the present study the distal attachment of the ATTL had insertions to the talar body, neck or close to the neck. Furthermore, the shape of the medial surface of the talus can be confusing in determining the boundaries of the neck: the method used in the current study was more accurate in identifying the exact site of distal attachment.

The method used was to determine the distance and angle between the mid distal ATTL attachment and the posteromedial tubercle of the talus. The single ATTL had the mid distal attachment 19.53 ± 3.71 mm from the posteromedial tubercle, forming an angle of 27° ± 7°: the distance was significantly greater in males (21.95 ± 3.12 mm) compared to females (17.95 ± 3.21 mm), being positively correlated with both foot length and 1st metatarsal length, but negatively correlated with age thus supporting the aging theory concerning the morphology of the ligament. The angle between the distal ATTL attachment and the posteromedial tubercle was negatively correlated with ATTL length. This might be expected since as when the ligament becomes longer the distal attachment becomes more distal leading to a decrease in angle.

5.6.2.5 Anterior Tibiotalar Ligament (ATTL) Dimensions

The anterior tibiotalar ligament (ATTL) in the present study had a length of 10.15 ± 3.55 mm, similar to that reported by Milner and Soames (1998a) (11.5 ± 3.6 mm), Wenny et al. (2014) (8.35 ± 2.31 mm) and Campbell et al. (2014) (12 mm). However, Mkandawire et al. (2005) reported the length as 24.9 ± 8.03 mm, Boss and Hintermann (2002) 16.1 ± 6.8 mm, Luo et al. (1997) 19.6 ± 2.2 mm and Cromeens et al. (2015) 14.5 ± 3.2 mm. One possible explanation for the differences could be the embalming technique used which might affect the ligament dimensions. For example, Cromeens et al. (2015) and Boss and Hintermann (2002) used frozen specimens, while Mkandawire et al. (2005) used fresh specimens. Mkandawire et al. (2005) used specimens with an age range 26 – 94 years, while the age range in the current study was 62 – 98 years. Younger specimens may influence the dimensions of the ATTL: unfortunately, no studies have compared the morphology of the ankle ligaments in young and older individuals. Finally, the differences may also be due to differences in sample size: Luo et al. (1997) examined 7 specimens, Cromeens et al. (2015) and Boss and Hintermann (2002) 12 specimens, compared to the 36 specimens of single band ATTL in the current study. In the present study, the single ATTL length was greater in males (11.44 ± 3.98 mm) compared to females (9.11 ± 2.86 mm). In addition, length was positively correlated with all other dimensions suggesting a balance between all ligament dimensions in order to enable it to function efficiently and effectively.

In the two band form, the AATTL and PATTL had lengths of 9.42 ± 2.93 mm and 11.61 ± 3.27mm respectively, with a positive correlation between the lengths being observed. Furthermore, AATTL length was positively correlated with its distal width, while PATTL length was positively correlated with its proximal width.

The proximal, middle and distal width of the ATTL in the current study were 3.61 ± 1.78 mm, 3.06 ± 1.51 mm and 4.83 ± 2.8 mm respectively. Comparing the middle width with previous investigations it is in close agreement with Cromeens et al. (2015) (3.4 ± 0.6 mm), but is less than that reported by Milner and Soames (1998a) (6.5 ± 2.5 mm). In the present study, the ATTL was widest distally, with the proximal part wider than the middle part: ATTL proximal, middle and distal width were positively correlated with the ATTL PBA, NBA and DBA respectively. This suggests a balance between ligament width and the bony attachment lengths to provide appropriate stabilisation during movement. In the two band form AATTL width was 2.46 ± 0.8 mm (proximal), 2.84 ± 1.72 mm (middle) and 3.88 ± 1.84 mm (distal), with the distal width being significantly wider.

In the current study ATTL thickness was 0.76 ± 0.43 mm, considerably less than that reported by Boss and Hintermann (2002) (1.2 ± 0.7 mm), Cromeens et al. (2015) (1.2 ± 0.5 mm) and Butler and Walsh (2004) (2.5 ± 0.8 mm). The differences might be due to the fact that the latter studies used frozen specimens compared to formalin embalmed specimens in the current study, which may have had an effect on ligament structure and its dimensions. Furthermore, these studies used small sample sizes, between 7 and 12 specimens, compared to 38 specimens with a single ATTL in the current study, again, rather smaller than the current study. In the present study, ATTL thickness was positively correlated with the foot length, 1st metatarsal length; ATTL length with the proximal and middle widths showing the importance of an appropriate thickness in relation to length and width. AATTL and PATTL thickness were 0.59 ± 0.36 mm and 0.68 ± 0.35 mm respectively, with AATTL thickness negatively correlated with age suggesting that aging and degenerative changes lead to fibre loss reducing the size of the ligament.

5.6.2.6 Anterior Tibiotalar Ligament (ATTL) Bony Attachment Lengths

Cromeens et al. (2015) and Boss and Hintermann (2002) reported the ATTL proximal attachment area, with Cromeens et al. (2015), Wenny et al. (2014) and Boss and Hintermann (2002) reporting its distal attachment area. None of these studies reported the proximal or distal bony attachment lengths. In the current study, the ATTL had bony attachment lengths of 2.52 ± 1.63 (PBA), 2.51 ± 1.9 mm (DBA) and 6.76 ± 2.21 mm (NBA) that comprised 21.37%, 21.29% and 57.34% of its length respectively. Bony attachment lengths of the AATTL in the two band form were 1.87 ± 0.9 mm (PBA), 2.52 ± 1.7 mm (DBA) and 6.91 ± 2.28 mm (NBA) comprising 16.55%, 22.30% and 61.15% of its length respectively, with AATTL DBA positively correlated with PATTL DBA suggesting a balance between the two distal bony attachments preserving the ability to respond equally to different forces. The PATTL had a PBA, DBA and NBA of

2.01 ± 1.36 mm, 2.44 ± 1.98 mm and 7.59 ± 2.22 mm respectively and comprised 16.69%, 20.27% and 63.04% of its length. A positive correlation between PATTL DBA and thickness suggests that a longer DBA requires a greater thickness in order to prevent its disruption. Knowing the proximal and distal bony attachment lengths provides surgeons with important anatomical details of how much of the ligament needs to be reattached in order to facilitate normal functioning without damage.

5.7 Ankle Collateral Ligaments: Functional Aspects

5.7.1 Anterior Talofibular Ligament (ATFL) Behaviour during Movement

In the present study the length of the ATFL in was significantly longer in plantarflexion and inversion compared to the neutral position, but significantly shorter in dorsiflexion and eversion. Consequently, the ATFL is most taut in plantarflexion, agreeing with previous investigations (Miller and Thompson, 2015; Ozeki et al., 2002; Raheem and O'Brien, 2011; Bahr et al., 1998; Sarrafian, 1993a; Nigg et al., 1990), as well as being stretched in inversion agreeing with Bahr et al. (1998) and Colville et al. (1990), but relaxed in dorsiflexion in agreement with Ozeki et al. (2002) and Raheem and O'Brien (2011), as well as in eversion. The present study suggests that the ATFL restricts plantarflexion and thus agrees with previous studies (Palastanga et al., 2006; Rasmussen, 1985; Rasmussen et al., 1983a): it also has an important role in limiting inversion, agreeing with Nordin and Frankel (2001), Bahr et al. (1998) and Kaneko (1985). Furthermore, the current study found that the maximum elongation of the ATFL (2.34 mm) was similar to that reported by Siegler et al. (1988) (2.46 mm), but greater than that reported by Luo et al. (1997) (5 mm) and Ozeki et al. (2002) (1.56 ± 0.76 mm). These later differences could be the result of smaller sample sizes (Luo et al., 1997) or the measurement system used (Ozeki et al., 2002).

The length in plantarflexion increased by 7.55% similar to that reported by Buzzi et al. (1993) (8.9%), but greater than Renstrom et al. (1988) (3.3%). The latter calculated the difference in length between 10° dorsiflexion and 40°

plantarflexion which should give a greater length difference as the ATFL was shorter in dorsiflexion. In the present study the change in length was measured between maximal dorsiflexion (6°) to maximal plantarflexion (40°).

In the current study, the ATFL was the widest component of the LCL, but was significantly thinner than other components: this may affect its strength. Nigg et al. (1990) and Attarian et al. (1985a) both reported the ATFL being the weakest ligament, failing at 130 ± 63 N and 138.9 N respectively. In addition, Siegler et al. (1988) observed that the ATFL had a low ultimate load: its anterior location also contributed to its weakness.

Previous studies investigating the effect of transection of the lateral and medial collateral ligaments have provided important information, which together with morphological descriptions, enables a better understanding of the functional anatomy of these ligaments. An increased laxity in dorsiflexion, inversion and eversion has been reported after ATFL transection (Hollis et al., 1995; Johnson and Markolf, 1983). The increase in dorsiflexion may be due to the lateral malleolus being free from the ATFL allowing it to be more externally rotated or move laterally thus permitting the talus to slide more posteriorly into the ankle mortise. Eversion was also observed to increase, which might be due to dorsiflexion also occurring during the movement. The function of the ATFL as restricting eversion was reported by Leardini et al. (2000).

An increase in inversion would be expected as the current study found that the ATFL was significantly strained in inversion; furthermore, plantarflexion also occurs during the movement as significant talar tilt and talar adduction plantarflexion was reported by Rasmussen (1985). This could explain why

Shibata et al. (1986) reported anterior instability of the ankle when the ATFL was torn. In plantarflexion, the tibia becomes externally rotated (Nordin and Frankel, 2001): sectioning the ATFL showed an increase in tibial external rotation and adduction in plantarflexion (Cass et al., 1984). This can be explained by absence of the ATFL insertion into the talus laterally leading to greater internal rotation of the talus, which is connected medially to the tibia by the deltoid ligament allowing the tibia to become more externally rotated.

In plantarflexion, there is talar internal rotation (Bonnel et al., 2010; Norkus and Floyd, 2001) and talar adduction (Bonnel et al., 2010), with the ATFL orientated anterosuperiorly in most cases and also taut in plantarflexion. The ATFL is attached distally to the anterior part of the talar body suggesting that it may resist talar internal rotation and adduction in plantarflexion. The distal attachment of the ATFL to the talus might be why the ATFL prevents lateral talar tilt (Sarrafian, 1993a) or talar anterior displacement (Nordin and Frankel, 2001; Sarrafian, 1993a, Rasmussen, 1985). In addition, the ATFL distal insertion to the anterior part of the talar body, being anteromedial to the anterolateral malleolar line (ALML) during plantarflexion, may provide a limitation to talar internal rotation (Hockenbury and Sammarco, 2001; Sarrafian, 1993a) or adduction (Rasmussen, 1985), as well as varus tilt in both dorsiflexion and plantarflexion (Palastanga et al., 2006). Moreover, Sarrafian (1993a) demonstrated that the ATFL functions in limiting fibular external rotation: this may be due to its proximal attachment to the anterior border of the lateral malleolus of the fibula.

In the current study, the ATFL crossed medially from the lateral malleolus to the talus, with an anterosuperior (93.3%), anteroinferior (3.3%) or horizontal anterior (3.3%) projection in neutral, plantarflexion and inversion. This contradicts Luo et al. (1997) who reported that the ATFL was orientated anteriorly, inferiorly and medially in neutral. However, in the present study the ATFL was taut in plantarflexion and inversion, therefore the anterosuperior orientation of the ATFL seen in the majority of specimens may help minimise talar internal rotation and talar adduction that occurs in plantarflexion. The ATFL had anterosuperior (96.7%) or anteroinferior (3.3%) orientations in dorsiflexion and eversion.

Vogel (1970) reported that the superior band of the ATFL was taut in plantarflexion, while the inferior band was taut in both dorsiflexion and plantarflexion (as cited by Sarrafian, 1993a). In the current study the length of the inferior and middle bands of the ATFL did not differ compared to their length in neutral. This suggests that these two bands have an isometric function, even though the ATFL is considered an anisometric ligament (Renstrom et al., 1988). There are reports in the literature that the posterior fibres (Renstrom et al., 1988) and central and distal fibres of the ATFL have isometric actions.

5.7.2 Calcaneofibular Ligament (CFL) Behaviour during Movement

It was observed in the current study that the CFL was significantly longer in dorsiflexion but significantly shorter in plantarflexion and inversion compared to neutral: there was no difference in the length in eversion, suggesting that it is most taut in dorsiflexion. Bahr et al. (1998), Luo et al. (1997), Cawley and France (1991) and Nigg et al. (1990) all reported that the CFL was most taut in dorsiflexion and inversion. The current study confirms this for dorsiflexion, but not for inversion when the ligament was relaxed compared to dorsiflexion and neutral. In contrast Sarrafian (1993a) reported the CFL to be shortened and relaxed in plantarflexion and not always taut in dorsiflexion. The current study observed that in 16 specimens CFL length in inversion was longer compared to neutral, suggesting that the CFL may have a role in resisting movements such as inversion, as it involves calcaneal movement at the subtalar joint to which the CFL attaches distally. In 9 specimens in the present study the CFL was longer in plantarflexion than in neutral: this could be due to variation in its distal attachment (Sarrafian, 1993a) or to its different morphologies (Ruth, 1961). Nevertheless, in the present study the CFL was most taut in dorsiflexion, with its length in neutral significantly longer than in plantarflexion. Renstrom et al. (1988) reported no strain in the CFL in neutral, the ligament being isometric, which might also be the case in the current study in plantarflexion as no strain was observed. The CFL therefore appears to be complex in term of its strain behaviour: this might be due to its proximal attachment to the anterior border of the lateral malleolus resulting in the ligament curving proximally during plantarflexion, when its attachment to the calcaneus is inferior and posterior to the anterior border of the lateral malleolus. This would support the views of Sarrafian (1993a) and Ruth (1961) who stated that the shape of the ligament affects strain in different joint positions. Further investigation into the ligament’s behaviour is encouraged to clarify this.

Raheem and O'Brien (2011) observed a shorter CFL length compared to the current study, with the length in dorsiflexion being longer than in plantarflexion. This difference may be due to how length was measured as no clear methodology was described. In the current study length was measured from the extreme points of attachment of the ligament proximally and distally. Raheem and O'Brien (2011) also had a smaller sample size (n = 20) compared to the current investigation (n = 51).

Sarrafian (1993a) demonstrated that the CFL acted on both the ankle and subtalar joints as it had a proximal attachment to the lateral malleolus and a distal attachment to the calcaneus, as was observed in the present study. The calcaneofibular ligament mainly restricts dorsiflexion and becomes slightly elongated in neutral and eversion. However, Stephens and Sammarco (1992) reported that the CFL stabilises the ankle joint during all movements, which may explain the variations reported in previous studies as well as the current study. It is suggested that the CFL proximal attachment to the anterior border of the lateral malleolus changes the position and shape of the origin in different movements, which modifies its length as observed in the present study. Thus changes in CFL length should be interpreted with caution as it appears to stabilise the ankle joint in all positions.

Restricting inversion was observed in the current study and is therefore considered to be one role of the CFL as reported by Nordin and Frankel (2001), particularly in dorsiflexion as confirmed in the present investigation. The CFL is considered an important stabiliser of the subtalar joint (Weindel et al., 2010; Sarrafian, 1993b; Kjaersgaard-Andersen et al., 1987a) because of its attachment to the calcaneus, which moves during subtalar movement, hence the involvement of the CFL in ankle sprains (Weindel et al., 2010). Palastanga et al. (2006) and Kaneko (1985) both reported that the CFL limits talar abduction, while Sarrafian (1993a) demonstrated that it limits talar tilt in dorsiflexion while the ATFL undertakes this role in plantarflexion. This can be explained by the lateral location of the CFL, as well as it is actively functioning in dorsiflexion, while the ATFL functions in plantarflexion to limit talar tilt. In dorsiflexion, the lateral malleolus moves laterally (Kärrholm et al., 1985) and/or is externally rotated (Mulligan, 2011; Close, 1956; Barnett and Napier, 1952). Since the CFL has a large proximal attachment to the anterior border of the lateral malleolus and becomes stretched in dorsiflexion, it could have a role in restricting fibular abduction or external rotation when the ankle is dorsiflexed.

In the present study the maximum CFL elongation was 2.18 mm, less than the 3.66 ± 0.71 mm stated by Siegler et al. (1988), the 1.47 ± 0.65 mm by Ozeki et al. (2002) and the 5.1 ± 2.9 mm by Luo et al. (1997), who reported the change in inversion: Luo et al. (1997) also reported a smaller change of 1.9 ± 0.8 mm in dorsiflexion. In addition, the present study found that CFL length in dorsiflexion was greater than in neutral, which contradicts Ozeki et al. (2002): their study used a strain transducer system to measure CFL change in 12 fresh frozen ankles, compared to the current study which used digital callipers to measure the physical change in 51 formaldehyde embalmed ankles. In the current study, during dorsiflexion the maximum increase in CFL length was 7.5% from that of plantarflexion and 1.99% from that of neutral; Ozeki et al. (2002) reported the maximum change as 5.3%.

In the current study, the CFL was wider distally and had 28.75% of its length attached distally to the calcaneus (DBA). It was also thick giving the strength to resist force compared to the ATFL. This is in line with previous reports that found that the CFL failed at 345.7 N (Attarian et al., 1985a) and 296 ± 31 N (Nigg et al., 1990). Furthermore, Siegler et al. (1988) demonstrated that the CFL high ultimate load, as well as the axial orientation of its fibres and density were all factors that made it a strong ligament. In the present study, the CFL crossed medially from the lateral malleolus to the calcaneus and was orientated posteroinferiorly in all joint positions, which agrees with Boonthathip et al. (2011), Kitsoulis et al. (2011) and Taser et al. (2006). This orientation provides good stability and resistance to traction forces from the calcaneal distal attachment in maximum dorsiflexion.

Rasmussen (1985) and Cass et al. (1984) demonstrated that when the CFL was disrupted the tibia became more adducted, together with an increase in tibial external rotation (Cass et al., 1984). This can be explained as follows: damage to the CFL may lead to a loss of connection between the fibula and calcaneus normally provided by the CFL attachments, giving the tibia more opportunity to externally rotate in the mortise: this was observed when both the ATFL and CFL were disrupted. However, Erduran and Havıtçıoğlu (2011) report that sectioning the CFL does not significantly affect ankle movement if the ATFL had previously been sectioned. The distal attachment of the CFL to the lateral surface of the calcaneus enables the ligament to stabilise the subtalar joint in association with other talocalcaneal ligaments. This was confirmed by Martin et al. (1998, 2002), who showed the importance of the CFL in stabilising the subtalar joint and decreasing the loading on the cervical ligament. Thus trauma to both the ATFL and CFL may cause ankle and subtalar joint instability (Shibata et al., 1986).

5.7.3 Posterior Talofibular Ligament (PTFL) Behaviour during Movement

In the current study it was not possible to measure PTFL length in plantarflexion and inversion as these movements push the talus anteriorly while the inferior tibiofibular complex descends posteroinferiorly to cover the PTFL behind the talus. Nevertheless, it was observed visually to be more relaxed in these two positions. However, the length of the PTFL in the current study in dorsiflexion and eversion were greater than in neutral, with the difference between neutral and dorsiflexion being significant. This shows that dorsiflexion causes the PTFL to stretch, being in agreement with Ozeki et al. (2002) and Luo et al. (1997). However, Vogel (1970) reported that only the posterior fibres of the PTFL are stretched in dorsiflexion, while the anterior fibres are stretched in all joint positions. Elongation of the PTFL from neutral to dorsiflexion was 0.76 mm, close to that reported by Ozeki et al. (2002) (0.67 mm), but less than that observed by Siegler et al. (1988) (3.48 mm).

In the current study a significant elongation of the PTFL in dorsiflexion was observed suggesting its important role in limiting this movement: this is in agreement with previous studies (Palastanga et al., 2006; Ozeki et al., 2002; Luo et al., 1997; Valmassy, 1996). Furthermore, Kapandji (1989) demonstrated its role in transferring eversion tension from the fibula to the talus, possibly due to its long attachment to the talus. This long distal attachment was observed in the current study and appears to play an important role in preventing the talus from being displaced posteriorly, as suggested by Sarrafian (1993a) and Siegler et al. (1988). In dorsiflexion the talus is pushed posteriorly into the ankle mortise, with the PTFL appearing to limit this displacement. In dorsiflexion, the fibula is usually abducted (Kärrholm et al., 1985) or externally rotated (Mulligan, 2011; Close, 1956; Barnett and Napier, 1952) suggesting that the attachment of the PTFL to the fibular malleolar fossa limits such movement. In addition, the PTFL may have a role in limiting anterior displacement of the talus as well as talar external rotation, as demonstrated by Sarrafian (1993a) or talar abduction. Most ankle sprains however do not involve the PTFL, while talar tilt or anterior displacement has been observed in patients with ATFL and CFL injuries: the PTFL functions to minimise such talar movements but not completely. This is supported by Rasmussen (1985) who stated that the PTFL is not an independent stabiliser of the ankle joint, but provides a supplementary action. In addition, Butler and Walsh (2004) justified why the LCLs are three separate ligaments compared to the deltoid as being due to the increased motion and rotation on the lateral side of the talus putting higher strains on the LCLs.

In the present study PTFL dimensions gave an indication of the stability and strength of the ligament. Firstly, it had wide proximal and distal attachments, as well as being the thickest of the LCL components. It also had 73.17% of its total length attached to the fibular malleolar fossa and talar posterior surface providing stability and fixation of the ligament. In addition, Siegler et al. (1988) reported that the PTFL high ultimate load, its thickness, posterior location to the ankle and the lateromedial orientation of its fibres are all factors that give it the required mechanical properties to limit ankle dorsiflexion and prevent the talus from being medially or posteriorly displaced. In the present study the PTFL crossed medially from the malleolar fossa of the lateral malleolus to the posterior talus in an posteroinferior direction in all joint positions, thus agreeing with Luo et al. (1997), who reported PTFL orientation in neutral as posterior and inferior. However, it disagrees with Courvoisier et al. (2008) who demonstrated that the PTFL posterior part runs medially and inferiorly, and with Taser et al. (2006) who reported the PTFL to pass in a horizontal posteromedial direction.

Transection of the PTFL generally increases dorsiflexion and tibial external rotation (Rasmussen, 1985), while sectioning the PTFL and CFL showed increases in both adduction and external rotation (Rasmussen, 1985; Cass et al., 1984). The increase in dorsiflexion is expected as the current study observed that the PTFL restricts dorsiflexion, while tibial adduction may result from loosening of the long PTFL attachment on the talus causing it to move medially, while the tibia, which is connected to the talus by the deltoid, is not pulled laterally by the talus. Rasmussen et al. (1983b) demonstrated that the PTFL has an important function in limiting dorsiflexion, talar tilt and internal and external talar rotation when both the ATFL and CFL are disrupted. The long posterior attachment of the PTFL on the posterior surface of the talus appears to stabilise the talus posteriorly, thereby decreasing talar tilt and rotation.

Palastanga et al. (2006) reported that sectioning the ATFL, the CFL together with the PTFL may lead to an increase in dorsiflexion, internal rotation and external rotation of the talus, especially in dorsiflexion. Rasmussen and Tovborg-Jensen (1982) reported that sectioning one part of the LCL may not have an effect on dorsiflexion; however the current study suggests that the PTFL limits dorsiflexion as well as talar tilt and posterior displacement.

5.7.4 Superficial Layer of the Medial Collateral Ligaments (Deltoid)

5.7.4.1 Tibionavicular Ligament (TNL) Behaviour during Movement

In the present study the tibionavicular ligament (TNL) was significantly longer in plantarflexion and inversion, but significantly shorter in dorsiflexion and eversion compared to neutral. Being taut in plantarflexion agrees with Pankovich and Shivaram (1979a). In the present study in plantarflexion the TNL elongated 13.71 mm and 10.57 mm from dorsiflexion and neutral respectively, greater than that reported by Luo et al. (1997) (5.6 ± 0.41 mm); however Luo et al. (1997) only examined 11 specimens compared to the 41 specimens in the current study. Furthermore, Luo et al. (1997) did report a significant difference in TNL length between plantarflexion and dorsiflexion, as observed in the current study: they also reported a significant difference in TNL length between plantarflexion and inversion, an observation not found in the present study.

The present study suggests that the TNL limits plantarflexion, thus agreeing with Sarrafian (1993a), as well as limiting inversion. In addition, Palastanga et al. (2006) reported that it has a role in limiting talar abduction, while Sarrafian (1993a) demonstrated that it restricts talar external rotation. Limiting talar abduction and external rotation might be a result of the talar attachment of the TNL to the medial side, thus preventing the talus from sliding laterally (abduction) or rotating toward the fibula (external rotation). The tibia was found to be rotated externally in plantarflexion (Nordin and Frankel, 2001): since the TNL is attached to the medial malleolus of the tibia, as well as being taut in plantarflexion, this may limit external rotation of the leg; while the distal attachment restricts the internal rotation and adduction of the talus

In the present study the TNL was widest at its middle of all LCL and MCL components; however, it was also the thinnest. The TNL had a wide attachment to the talus and navicular, as well as blending with the spring ligament which may compensate for its thinness. It has been reported to be the weakest band of the deltoid ligamentous complex (Pankovich and Shivaram, 1979a). In the current study the TNL passed from the medial malleolus laterally to the navicular, and it had two orientations in all specimens: the posterior part was orientated anteroinferiorly and the anterior part anterosuperiorly. Palastanga et al. (2006) noted this unusual orientation as running anteriorly and downwards and then backward, while attaching to the spring ligament, while Pankovich and Shivaram (1979a) described the TNL as a fan shaped triangular band. The TNL was observed to be widely separated in shape and orientation, while blending with the joint capsule may decrease the strain on the ligament and restrict its disruption.

5.7.4.2 Tibiospring Ligament (TSL) Behaviour during Movement

The length of the tibiospring ligament (TSL) in the current study was not significantly different in any joint position suggesting that it functions isometrically to stabilise the ankle joint, as well assisting the spring ligament in supporting the head of the talus inferiorly. However, Siegler et al. (1988) reported that the TSL had a maximum elongation of 6.48 ± 1.4 mm contradicting the present study. There are differences between the two studies in that Siegler et al. (1988) examined 20 fresh specimens that were dissected and then frozen, while the current study examined 49 formaldehyde embalmed specimens. The embalming method may have affected elongation of the ligament fibres, therefore both sets of results should be interpreted with caution.

The observations of the current study suggest that the TSL is a stabiliser in all joint positions. In addition, its wide spreading distal attachment to the spring ligament may strengthen the parts of the spring ligament that lie below the head of the talus, thus supporting Sarrafian (1993a) who stated that the TSL was attached to and supported the spring ligament against gravity and pressure from the talar head; this may occur due the TSL distal attachment being blended with the spring ligament the surround the talar head.

The current study found that the TSL had a wide distal attachment to the spring ligament, which may give it better support and fixation distally. As the distal attachment is not bony this may give some flexibility for the ligament to receive high loads. Siegler et al. (1988) reported that the TSL has a high ultimate load (432 ± 307 N) making it the strongest part of the superficial deltoid. In addition, in the present study the TSL passed laterally from the medial malleolus to its distal attachment, with an anteroinferior orientation observed in the majority of specimens in neutral (82.1%), dorsiflexion (85.7%) and eversion (82.1%), while a posteroinferior orientation was observed in plantarflexion (75.9%) and inversion (75%). In dorsiflexion and plantarflexion, the TSL may help resist the tibial internal and external rotation that occurs in dorsiflexion and plantarflexion respectively. Quiles et al. (1983) reported that when the TSL is disrupted in association with the TNL there was an increase in the range of eversion, as well as laxity in the ATFL. This might be because together they comprise the anterior part of the medial collateral ligament, which may affect the ATFL as it is the anterior part of the lateral collateral ligament.

5.7.4.3 Tibiocalcaneal Ligament (TCL) Behaviour during Movement

Compared to the neutral position, TCL length in plantarflexion and inversion was significantly shorter, with there being no difference in dorsiflexion or eversion. Dorsiflexion length was significantly greater than plantarflexion length, while eversion length was significantly longer than inversion length. Therefore, the TCL is most taut in neutral, dorsiflexion and eversion, and relaxed in plantarflexion and inversion; this disagrees with Ozeki et al. (2002) who reported the neutral position as having the highest strain which decreased in both dorsiflexion and plantarflexion. In addition, the findings of the current study are contrary to those of Pankovich and Shivaram (1979a) who reported that the majority of TCL fibres were taut in plantarflexion. On further investigation in the current study 3 specimens had a longer TCL in plantarflexion compared to neutral, while 6 specimens had a longer TCL in plantarflexion compared to dorsiflexion. If the TCL is taut in plantarflexion it suggests that it is functioning isometrically, especially as it is acting across both the ankle and subtalar joints. Furthermore, the variable distal attachments, which include the talus, calcaneus and spring ligament, also support the TCL having isometric characteristics, as demonstrated by Bruns and Rehder (1992).

The findings from the current study suggest that the TCL limits excessive dorsiflexion, agreeing with Andersen et al. (1989) (as cited by Rasmussen et al., 1983a), as well as restricting excessive eversion at the ankle and subtalar joints, agreeing with Sarrafian (1993a). The ligament also appears to function in neutral. In addition, Palastanga et al. (2006) and Kjærsgaard-Andersen et al. (1989) stated that the TCL had a role in restricting talar abduction, as well as stabilising the talus medially (Kjærsgaard-Andersen et al., 1989). This might be a result of the distal TCL attachment into the talar medial surface or the talar posteromedial tubercle.In the present study the TCL was one of the medial ligaments that crossed both the ankle and subtalar joints, thus providing stability to both joints. Sarrafian (1993b) demonstrated the importance of the TCL as an additional supporter of the subtalar joint. In addition, Wirth et al. (1978) reported it to have a role in restricting plantarflexion, although this was not confirmed in the current study. Bruns and Rehder (1992) commented on the isometric function of the ligament. In the current study the TCL was taut in dorsiflexion and eversion, with its proximal attachment on the medial surface of the medial malleolus potentially limiting internal tibial rotation. As observed in the current study the TCL had a distal attachment to the medial surface of the talus and/or the talar posteromedial tubercle in 43.1% of specimens, thus it may resist external rotation of the talus which tends to occur in dorsiflexion.

Luo et al. (1997) reported that the TCL had a change of length of 2.6 ± 1.1 mm and 1.8 ± 0.8 mm in dorsiflexion and eversion respectively, which is greater than the 0.17 mm in dorsiflexion and 0.08 mm in eversion in the current study. The maximum change in TCL length reported by Ozeki et al. (2002) was 1.5 ± 0.69 mm, less than that observed in the present study (3.79 mm). Siegler et al.

(1988) described the TCL as not strong component of deltoid, having a low ultimate load (< 44.5 N), with the TSL reported to be the strongest component of the superficial MCL.

In the present study the TCL passed laterally from the medial malleolus to its distal attachment, with different orientations according to joint position. In neutral it had passed anteroinferiorly (25%), posteroinferiorly (60.7%) and inferiorly (14.3%), while in dorsiflexion it passed anteroinferiorly (27.6%), posteroinferiorly (37.9%) and inferiorly (34.5%). In plantarflexion it passed anteroinferiorly (6.7%) and posteroinferiorly (93.3%); the inversion it passed anteroinferiorly (6.9%) and posteroinferiorly (93.1%); in eversion it passed anteroinferiorly (21.4%), posteroinferiorly (39.9%) and inferiorly (39.3%). These observations do not agree with other studies: Palastanga et al. (2006) and Sarrafian (1993a) both described the TCL as being vertical, while Pankovich and Shivaram (1979a) reported it as perpendicularly orientated, however there was no specification of direction. Luo et al. (1997) described TCL orientation as inferior, lateral and posterior in 60.7%, 37.9%, 93.3%, 93.1% and 39.9% in neutral, dorsiflexion, plantarflexion, inversion and eversion respectively.

5.7.4.4 Superficial Tibiotalar Ligament (STTL) Behaviour during Movement

Superficial tibiotalar ligament (STTL) lengths in neutral, dorsiflexion and eversion were similar and greater than in plantarflexion and inversion showing that in neutral, dorsiflexion and eversion it was more taut compared to plantarflexion and inversion. The STTL component of the medial (deltoid) ligament has been rarely described in the literature, possibly due to the discrepancy in reporting its existence. Pankovich and Shivaram (1979a) were the only others to state that the STTL becomes taut in dorsiflexion, agreeing with the current study. The observations of the current study suggest a role for the STTL in resisting dorsiflexion and eversion, as well as acting as a joint stabiliser in neutral. The role of the STTL has not been previously considered as in many cases it is confused with the deep posterior tibiotalar ligament. A taut STTL in dorsiflexion and eversion resists tibial internal rotation, while its distal attachment to the talus may resist talar external rotation and abduction.

In the present study, the STTL passed slightly laterally from its proximal to distal attachments having a posteroinferior orientation in 96.4%, 89.3%, 100%, 100% and 92.6% of specimens in neutral, dorsiflexion, plantarflexion, inversion and eversion respectively: in the remaining STTLs it had a vertical inferior orientation. A posteroinferior orientation was reported by Cromeens et al. (2015). Sectioning the superficial component of deltoid led to an increase in talar external rotation (Padovani, 1975; as cited by Rasmussen et al., 1983a), due to the distal attachment sites of the TNL and STTL providing a medial pulling force that limits external talar rotation, especially in dorsiflexion.

5.7.5 Deep Layer of the Medial Collateral Ligaments (Deltoid)

5.7.5.1 Posterior Tibiotalar Ligament (PTTL) Behaviour during Movement

The APTTL length in neutral was significantly shorter than in dorsiflexion but longer than in plantarflexion and inversion, and no difference in eversion. Similarly, MPTTL and PPTTL lengths in neutral were significantly shorter than in dorsiflexion but significantly longer than in plantarflexion and inversion, with no difference in length between neutral and eversion. These observations suggest that all parts of the PTTL become taut in dorsiflexion compared to plantarflexion and inversion: in addition, in neutral and eversion it was significantly stretched compared to plantarflexion and inversion.

Being taut in dorsiflexion agrees with Pankovich and Shivaram (1979a). The maximum changes in length of the APTTL, MPTTL and PPTTL were 3.93 mm, 5.09 mm and 6.38 mm respectively, being greater than reported by Siegler et al. (1988) (3.1 ± 0.81 mm) and Luo et al. (1997) (2.6 ± 1.1 mm). Both Siegler et al. (1988) and Luo et al. (1997) had smaller sample sizes in addition to which Siegler et al. (1988) also examined fresh specimens that were then frozen after exposing the ligaments: this may have affected the flexibility of the fibres in their studies.

The current study confirms that the PTTL is a wide ligament and is the thickest component of the medial complex. Furthermore, the APTTL, MPTTL and PPTTL had 49.05%, 33.93% and 51.12% of their length attached proximally and distally. Siegler et al. (1988) also reported that the PTTL was the thickest and stiffest ligament of all collateral ligaments, which is in contrast to the present study as the PTFL was the thickest and the PTTL was the next thickest. The PTTL was also found to have a high ultimate load of 467 ± 209 N (Siegler et al., 1988). Therefore, it is suggested that these anatomical and functional characteristics may provide the ligament with the appropriate biomechanical characteristics to make it stiff and strong, as well as being a firm stabiliser of the ankle joint.

The observations of the current study suggest that all parts of the PTTL play a role in limiting dorsiflexion and eversion, as well as stabilising the ankle in neutral. Palastanga et al. (2006) reported that in addition, the PTTL also resists dorsiflexion. During dorsiflexion the tibia rotates internally (Nordin and Frankel, 2001; Close, 1956); therefore, a tense PTTL in dorsiflexion may help limit internal tibial rotation. Similarly, the distal attachment of the PTTL to the medial surface of the talus may minimise posterior sliding of the talus during dorsiflexion. Additionally, the PTTL distal attachment may also play role in limiting talar external rotation in dorsiflexion, agreeing with Parlasca et al. (1979), and talar abduction. Furthermore, Parlasca et al. (1979) demonstrated that the PTTL limits talar internal rotation in plantarflexion because of its strong, wide and long bony distal attachment to the medial surface of the talus that provides an opposite force to talar internal or medial rotation. Internal rotation of the talus usually occurs in plantarflexion (Bonnel et al., 2010; Norkus and Floyd, 2001), at which point the ligament is not stretched but relaxed with the posterior parts being folded: it would therefore have no effect in resisting rotational movement of the talus.

The APTTL passed laterally from the medial malleolus to its distal origin with a posteroinferior orientation in neutral (88.9%), dorsiflexion (81.5%), plantarflexion (100%), inversion (100%) and eversion (80%), and a vertical inferior orientation in neutral (11.1%), dorsiflexion (18.5%) and eversion (20%). The posteroinferior orientation appears when the ankle is dorsiflexed as the talar distal attachment posteriorly and the tibial proximal attachment move anteriorly causing the highest strain. This posteroinferior orientation of the ligament was also reported by Luo et al. (1997).

. Sectioning the superficial and PTTL deep component of the deltoid may result in an increase in both external and internal rotation of the talus (Rasmussen et al., 1983a; Parlasca et al., 1979), although Sasse et al. (1999) reported a decrease in external rotation in dorsiflexion and in internal rotation in plantarflexion. Hintermann and Golanó (2014) suggested that studies that section different ligaments to determine their function may not be reliable due to a number of factors, including inconsistent results, jeopardising the accuracy of the evaluation as specific ligaments or layers are usually sectioned before others possibly giving false information in evaluating the causes of instability.

5.7.5.2 Anterior Tibiotalar Ligament (ATTL) Behaviour during Movement

The length of the single band ATTL in neutral was significantly shorter than that in plantarflexion and inversion, but significantly longer than in dorsiflexion, and no different in eversion. Thus it was maximally stretched in plantarflexion and inversion and relaxed in dorsiflexion. There are no previous investigations which studied the change in length of the ATTL in different joint positions. In the two band form AATTL length in neutral was significantly longer than in dorsiflexion but significantly shorter than in inversion, and no different in plantarflexion or eversion. The PATTL in the two band form showed no difference in length in any joint position, suggesting that it has isometric characteristics or a guiding function.

The current study suggests that the single ATTL limits plantarflexion agreeing with Palastanga et al. (2006) and Rasmussen et al. (1983a), as well as inversion. In the two band form the anterior band appears to mainly limit inversion, while the posterior band provides guidance without elongation. The ATTL's role in stabilising the ankle and limiting plantarflexion and inversion may not be great compared to that of the ATFL or TNL. In plantarflexion or inversion, the proximal attachment of a tensed ATTL may limit tibial external rotation, while the distal attachment to the medial surface of the talus and the more common anteroinferior orientation may provide resistance to internal rotation of the talus.Rasmussen (1985) reported no change when the ATTL was sectioned with the TCL and TSL, compared to when the PTTL was also sectioned. However, Quiles et al. (1983) reported that sectioning the ATTL and superficial deltoid caused the distance between the origin and insertion sites of the superficial deltoid to increase. Such reports may not represent the precise role of the ATTL as they may not be accurate being dependent on the order of ligaments sectioned. The ATTL was a deeper band that could not be accessed unless part of the superficial layer had already been disrupted. The current study showed that the ATTL is a small ligament, being the shortest and narrowest of all collateral ligaments of the ankle. This may lead to it being considered unimportant as an ankle stabiliser as there are no data on its mechanical properties. Nevertheless, it was commonly observed in previous investigations, although because of its size it could have been easily missed or sectioned.

The ATTL passed laterally between its proximal and distal attachments with an anteroinferior orientation in neutral (83.3%), dorsiflexion (87.5%), plantarflexion

(79.2%), inversion (79.2%) and eversion (89.5%), or with a posteroinferior orientation in neutral (12.5%), dorsiflexion (8.3%), plantarflexion (20.8%), inversion (20.8%) and eversion (10.5%). The most common orientation (anteroinferior) agrees with Palastanga et al. (2006), Luo et al. (1997) and Pankovich and Shivaram (1979a), but is opposite to the most common orientation of the PTTL. Its orientation may help decrease the tension associated with plantarflexion and thus reduce the risk of the ATTL becoming disrupted. In the current study, an anteroinferior orientation was also seen in the AATTL in the two band form in all joint positions.

5.7.6 Role of the Ankle Collateral Ligaments

The current study provided morphological and functional information, which was used with the previous reports to analyse and draw conclusions on the role of the ankle collateral ligaments. However, many studies that investigated the ligaments and its role in different movements were not clear on the exact movement that occur; many reports do not specify the joint at which the movement occurs, such as internal and external rotation or abduction and adduction. However, analysing the ligaments' morphology (exact bony attachment sites) as well as their behaviour in the different joint positions provided this study with the knowledge of the possible movements at the ankle which the collateral ligaments act to limit or restrict (Table 5.7). Middle and posterior parts of the lateral and medial collateral ligaments of the ankle (CFL, PTFL, TCL, STTL and PTTL) were found to be stretched and strained in dorsiflexion, while the anterior parts (ATFL, TNL and ATTL) were taut in plantarflexion; however, this disagrees with Soames (2003) who stated that both dorsiflexion and plantarflexion result in tension in the anterior parts of ankle collateral ligaments.

Table 5.7 Role of the ankle collateral ligaments: ATFL, anterior talofibular ligament; CFL, clacneofibular ligament; PTFL, posterior talofibular ligament; TNL, tibionavicular ligament; TSL, tibiospring ligamenr; TCL, tibiocalcaneal ligament; STTL, superficial tibiotalar ligament; PTTL, deep posterior tibiotalar ligament; ATTL, anterior tibiotalar ligament.

Movement Restricted	**Ligaments Acting to Restrict**
Dorsiflexion	CFL, PTFL, TCL, STTL, PTTL
Fibular abduction and external rotation	CFL, PTFL
Talar abduction and external rotation	PTFL, TCL, STTL, PTTL
Tibial internal rotation	TCL, STTL, PTTL
Plantarflexion	ATFL, TNL, ATTL
Talar adduction and internal rotation	ATFL, TNL, ATTL
Tibial external rotation	TNL, ATTL
Inversion	ATFL, TNL, ATTL
Eversion	CFL, TCL, STTL, PTTL
Talar posterior displacement	PTFL
Talar head support	TSL

5.8 Injuries to the Ankle Collateral Ligaments (Clinical Aspects)

5.8.1 Epidemiology and Mechanism of Injury

Ankle sprains are relatively common: everyday 5000 cases are reported in the UK and 28000 in the US (Adams et al., 2013, Geppert, 1998; as cited by Kumai et al., 2002); however there may be more cases not reported or referred to A&E.

In the current study, the morphology of the lateral and medial collateral ligaments of the ankle was comprehensively investigated; in addition, ligament behaviour and strain were investigated to provide a sound knowledge base for the functional anatomy of these ligaments. Therefore, the results of the present study can help in understanding the mechanism of injury that may occur to the ankle ligaments. For example, clinicians may need to understand the different mechanisms of injury to aid in diagnosing and defining the type of soft tissue trauma (ligaments) and/or fracture that has occurred (Okanobo et al., 2012). In general, an ankle sprain usually results from a plantarflexion (Ferri, 2016) or an inversion injury (Adams et al., 2013) and affects the lateral collateral ligaments (LCL), while an eversion injury affects the deltoid or parts of the tibiofibular ligaments (Ferri, 2016).

5.8.1.1 Lateral Collateral Ligaments

Injury to the lateral collateral ligaments comprises 79% (Gerber et al., 1998) to 85% (Ferri, 2016; Adams et al., 2013) of all ankle sprains, 65% of which solely affect the ATFL (Adams et al., 2013). The CFL is the second most common ligament to be injured combined with ATFL injury (Bortzman and Manske, 2011); isolated CFL injury is uncommon (Adams et al., 2013; Robbins and Waked, 1998; Francillon, 1962). Vulnerability of the ATFL to injury may be related to it being weak, thin and its course from anterior to medial to attach to the anterior part of the talar body. This location anterior to the ankle joint may increase the risk of it being disrupted when it is excessively strained, as in plantarflexion and inversion when the talus rotates internally creating a force that pulls on the distal attachment of the ATFL. In addition, one third of lateral malleolar avulsion fractures result in a torn ATFL (Broström, 1966). This may be due to the proximal attachment of the ATFL to the anterior border of the lateral malleolus. Furthermore, Browner et al. (2015) reported that the ATFL and PTFL may both be affected by fractures of the lateral talar process. However, in the current study the ATFL and PTFL were not attached directly to this process as reported by DiGiovanni et al. (2007), but attached between the two ligaments with fracture to the process causing disruption to the parts of the ATFL and PTFL near to the lateral talar process. The CFL is not as commonly injured as the ATFL which might be due to its morphological qualities compared to the ATFL. These qualities include its wide distal attachment to the calcaneus, the long DBA and its thickness, as observed in the current study, as well as its high load to failure, as reported by Nigg et al. (1990) and Attarian et al. (1985a). The ATFL and CFL are deliberately excised in surgery that aims to fix talar body fractures or in calcaneal comminuted fractures (Browner et al., 2015); therefore, repair of the ATFL and CFL following such surgery is performed.

Tears or disturbance of the ATFL and CFL may occur at any level, including its mid region, proximal or distal attachments (Coughlin et al., 2014). Therefore, understanding the possibility of their disturbance is important in understanding the mechanism of injury. For example, in proximal or distal avulsion fractures the morphology of the ligament needs to be understood in order to evaluate and surgically reconstruct the ligaments irrespective of the level of tear or disturbance. The PTFL has been reported to be rarely injured, and when it does occur it is combined with injury to the ATFL and CFL (Broström, 1964). This is to be expected as the PTFL is wide both proximally and distally and is the thickest of all LCL components, having 73.17% of its total length attached to the fibular malleolar fossa and talar posterolateral surface, as observed in the current study. Furthermore, the PTFL has a high ultimate load (Siegler et al., 1988) thus it is more difficult to damage.

5.8.1.2 Medial Collateral Ligaments (Deltoid) Ligament

The deltoid ligament has been reported in complex ankle injuries involving high external forces (Savage-Elliott et al., 2013, Robbins and Waked, 1998) causing excessive eversion (Hintermann et al., 2004). This may be explained by the medial location of the ligament with many parts of it under high strain in eversion and dorsiflexion. This was observed in the current study as the TCL, STTL and PTTL were under the highest strains in both dorsiflexion and eversion: with thinner ligaments, such as the TNL and ATTL, under strain in plantarflexion and inversion. In general, deltoid may undergo trauma as part of a complex injury to the ankle (Savage-Elliott et al., 2013), as well as to fractures of the lateral (Koval et al., 2007) or medial (Okanobo et al., 2012) malleoli when the ankle mortise is wider in the everted foot causing greater strain on the deltoid ligament. In addition, Browner et al. (2015) and O'Loughlin et al. (2009) reported that deltoid trauma can result from fracture of the neck of the talus and talar osteochondral lesions respectively. This may affect the ATTL and deep part of the TNL that attach to the talus near its neck. In addition, the STTL and PTTL are always attached to the talus and can be excessively externally rotated in extreme dorsiflexion and eversion, during which the deltoid will be highly strained and may be torn from the bone.

Other reported causes of deltoid rupture are insufficiency of the tendon of tibialis posterior resulting in overloading and straining of the ligament (Deland et al., 2004) or vice versa (Hintermann et al., 2004). It has been commonly observed that athletes with tibialis posterior tendon pathology also have a deltoid injury caused by an everted foot (O'Loughlin et al., 2009). As tibialis posterior is the main foot invertor (Palastanga et al., 2006), this can explain how a disturbance or pathology of the muscle or its tendon may result in weakness of inversion resulting in higher eversion of the foot creating additional strain on the deltoid in general and the TCL, STTL and PTTL in particular. Injury to deltoid may occur in combination with an LCL injury as was suggested by Hintermann et al. (2004), who reported that 77% of medial ankle instability cases had an LCL injury, suggesting that either the LCL or MCL caused overloading or overuse of the other as compensation. However, in general deltoid injuries are less common, but the finding by Hintermann et al. (2004) should be considered when routinely examining LCL injury. Surgery to fix the sustentaculum tali involves splitting deltoid and sectioning it at the sustentaculum tali for visualisation and minimising deltoid damage (Browner et al., 2015). It is suggested that an understanding of the morphology of the deltoid complex will enable better visualisation and approach in splitting the ligament, as well as for surgical repair.

The mechanism of injury of the lateral and/or medial collateral ligaments must be investigated by asking patients how the injury occurred and what the position their foot was in during the injury. This becomes more important as it is reported that accident and emergency doctorsdisregard ankle sprains, especially in cases when there is no fracture (Browner et al., 2015).

5.8.2 Treatment

The importance of correct diagnosis and treatment of ankle ligament injuries should be enforced, as misdiagnosis and treatment may lead to disability (Ferran et al., 2009) or osteoarthritis (Bortzman and Manske, 2011). However, the treatment of lateral and medial ligaments is controversial (Bortzman and Manske, 2011). Therefore, a more functional and standardised treatment regime to retain ligament function is suggested. Knowing the morphology as well as the function and behaviour of each part of these ligamentous complexes is important to provide a solid base from which a specific treatment should be considered.

5.8.2.1 Conservative (Non-Surgical) Treatment

Conservative treatment of ankle instability is more common and preferable as there have been results as good as surgical intervention (Ferri, 2016; Bortzman and Manske, 2011). However, when a ligament is completely disrupted, stability, as well as talar movements and the integrity of the ankle ligaments might be compromised especially when the torn parts of the ligaments are separated and there is little chance of healing. This is why surgical intervention is recommended when the symptoms of ankle instability persist (Ferri, 2016) or when there is restricting pain (Canale et al., 2016; Browner et al., 2015). Koval et al. (2007) reported that partial injury to the deltoid does not require surgery, whereas a complete tear requires surgical intervention, presumably because partial tears might heal without surgical repair.

5.8.3 Injured Lateral Collateral Ligaments (Surgical Treatment)

Two main approaches for surgically treating ATFL and CFL injuries are used: anatomical and non-anatomical (Baumhauer and O'Brien, 2002). Anatomical treatment involves either repairing the injured ligament or using a graft to mimic the injured ligament (Jung et al., 2012; Ferran et al., 2009), although all approaches lack strong evidence as to which is best for optimal results (Kennedy et al., 2012).

Knowing the distal anatomical attachments of the ATFL and CFL is important in reconstructing and retaining the function of these ligaments. However, surgeons may be misled by the complexity of the anatomical structures and have limited knowledge of some ligament surgical reconstructions. Jerosch et al. (2005) reported that surgeons were not able to identify the exact distal attachment site of the ATFL and CFL, with the investigation highlighting surgeons as a factor in determining the approach to reconstruction. Knowing and understanding the morphology of these ligaments and their proximal and distal attachment is important to surgically reconstruct or repair an injured ATFL and CFL: this was one aim of the current study.

5.8.3.1 Non-Anatomical Reconstruction (Reconstructive Tenodesis)

The Evans procedure showed limitations in movement and instability that developed later in many patients. As the tendon of fibularis brevis in this approach is not attached to the talus, this may give the talus the freedom to rotate or tilt, even if the tendon was placed lateral to the talus. This was supported by Colville et al. (1992), who reported that the Evans procedure may increase anterior displacement, internal rotation and talar tilt. In addition, the tendon does not mimic or replace the CFL, which has an attachment to the fibula or calcaneus and affects both ankle and subtalar joint movements.

In the Chrisman-Snook procedure the tendon might work as a CFL replacement; however, consideration of the site of distal attachment of the CFL to the calcaneus as well as its orientation is needed in order to provide the same or a similar function to the CFL. It appears that mimicking the CFL proximally is not accurate because as the tendon passes to the calcaneus it approaches from the posterior aspect of the lateral malleolus which is not the same morphology as the CFL. . In addition, Colville et al. (1992) reported that the Chrisman-Snook procedure resulted in an increase in anterior displacement and internal rotation of the talus.

The modified Watson-Jones approachmay need to be functionally evaluated to check if the approach is limiting the required motion of the talus: there is however no involvement or reconstruction of the area on which the CFL is acting at.

Non-anatomical approaches are claimed to lead to good results (Buerer et al., 2013), but subtalar movement restriction was reported and presented in all three approaches (Colville et al., 1992). Furthermore, ankle instability later developed in many patients who underwent these surgeries (Buerer et al., 2013). Ankle and subtalar ROM limitation has been reported in the literature (Baumhauer and O'Brien, 2002; Colville, 1998), while risking the function of the fibularis muscle or cutaneous nerves (Colville, 1998), although it has been reported that there is no significant change in eversion strength (Gillespie and Boucher, 1971).

5.8.3.2 Anatomical Repair (Modified Broström Procedure)

The effect of the extensor retinaculum that is attached to the fibula in the Broström approach on fibula rotation or in widening of the ankle has not been evaluated. Following the procedure, the foot is immobilised for 6 weeks in neutral position. In the present study the neutral position was found to be one in which the ATFL and CFL were neither maximally stretched nor relaxed. The procedure preserved the anatomy of the ATFL as much as possible, which in turn may preserve its function. However, when there is insufficient ligament to repair, as well as in cases of prior surgery and hypermobility, are factors that lead to failure of this approach (Karlsson et al., 1988a). Consequently, it is not suitable for every case as injuries to the ligaments vary.

5.8.3.3 Anatomical Reconstruction using Grafts

When ATFL and CFL status is inappropriate for repair anatomical reconstruction using grafts is recommended (Maffulli and Ferran, 2008). However, these techniques may mimic the course of the ATFL and CFL and may provide good restriction to movement, such as talar tilting. Unfortunately, patients were followed for a short period of time after the reconstruction in most cases. Jung et al. (2012) stated that all investigations of anatomical reconstructions using different grafts did not have long term outcomes, which are therefore still unknown and require further investigation. Other considerations include the holes and tunnels drilled in the fibula, talus and calcaneus which may cause more damage to the ankle joint by weakening the bones, with the fibula and neck of the talus being vulnerable to cracking or fracture. In addition, functional analysis should be carried out to confirm the role of the graft in providing appropriate stability and restriction at the ankle joint without limitation to movement. The current study suggests that longer term follow ups, as well as full biomechanical and functional assessment of the role of these graft in ankle stability and the effect of these approaches on the integrity of the bony complex of the ankle and subtalar joint, be conducted.

5.8.4 Injured Medial Collateral Ligament (Deltoid) (Surgical Treatment)

There is a lack of discussion of surgical reconstruction of the deltoid ligament in the literature (Deland et al., 2004). Some clinicians contend that an injured deltoid should not be surgically treated (Savage-Elliott et al., 2013), especially in fracture associated injuries (Stromsoe et al., 1995). However, Savage-Elliott et al. (2013) demonstrated the need for surgical reconstruction of deltoid ligament in cases of complex fracture and medial ankle instability; however, Canale and Beaty (2013) stated that the deltoid ligament cannot be as effectively reconstructed as the ATFL and CFL, suggesting that the shortness of the deep fibres of deltoid, as well as tension in the medial ankle structures, results in difficulty in achieving satisfactory results.

Shortening the ligaments to enable them to heal may be one technique used to reconstruct the MCL.

An important technique in the reconstruction of an injured deltoid ligament is the Deland approach which uses the proximal part of the tendon of fibularis longus, which is passed through the talus and tibia (Canale and Beaty, 2013; Deland et al., 2004). Reconstructing deltoid is also used to correct valgus deformity in advanced stage IV acquired flatfoot deformity (Jeng et al., 2011). Deland et al. (2004) and Ellis et al. (2010) both used the Deland procedure to correct such a deformity, with good results generally being reported. Hintermann et al. (1999) also corrected such a deformity either by repair or reconstruction.

The Deland approach provides a lateral pulling force to the talus, while the Jeng approach simply provides medial stability to the ankle joint. Nevertheless, the Deland et al. (2004) and Jeng et al. (2011) approaches do not cover the whole of the distal attachment of deltoid which spreads to the navicular, spring ligament, calcaneus and talar medial surface all of which aid medial stabilisation. The extensive hole drilling into the tibia, talus and calcaneus may put at risk the integrity of the ankle and subtalar joints resulting in stress fractures to the bones that comprise the ankle and/or subtalar joints; therefore, further investigation in this respect is encouraged. The approach outcomes were short term and as such the long term outcomes are not known. Finally, a comprehensive functional and biomechanical analysis of the way these various grafts work in providing the appropriate stabilisation to the ankle and subtalar joints is recommended to determine the efficacy of such approaches.

5.8.5 Anatomical Consideration in Surgically Repairing or Reconstructing Ankle Collateral Ligaments

The anatomy of the ankle LCL and MCL is important and essential for a successful surgical reconstruction. Knowing and understanding the anatomy of the LCL can help in understanding the mechanism of injury and subsequent surgical reconstruction of the injured ligaments (Van Den Bekerom et al., 2008), as well as helping to evaluate and treat the ligaments (Hertel, 2002). The present study provides a comprehensive solid base of anatomical knowledge that will help to create a better understanding of the mechanism of injury to these ligaments, as well as improved interpretation of LCL and MCL injury evaluation, radiological diagnosis and surgical repair or reconstruction. The morphology of each ligament was investigated and variations in the number of bands highlighted to provide surgeons with a better understanding of what is expected. Knowledge of the exact proximal and distal attachment sites of each ligament is essential in surgical reconstruction procedures (Van Den Bekerom et al., 2008). Jerosch et al. (2005) reported that 33 expert orthopaedic foot surgeons were unable to precisely identify the exact distal attachment of the

ATFL and CFL. Thus, anatomical detail is important to enhance the location of the anatomical origin and insertion of these ligaments (Taser et al., 2006; Burks and Morgan, 1994).

Knowing the ligament dimensions (length, width and thickness) may help in the assessment of how many fibres have been lost (Taser et al., 2006). Boss and Hintermann (2002) demonstrated that in surgically reconstructing the deltoid ligament knowing its dimensions may help in understanding the isometric locations, as well as limiting a possible loss of ROM. The current study reported ligament behaviour during different joint movements, including the change in length (elongation or shortening) and the morphological orientation of the ligament as it passes from its origin and insertion. An appreciation of this information will enable surgeons to gain a better visualisation of how the ligament should be orientated after reconstruction and what the expected behaviour of each ligament in each joint position is. Thus preserving that behaviour in order to maintain as much of the function, yet preventing joint limitation. In addition, the bony attachment lengths of the current study are important as they act as a guide to how much of the ligament should be free and how much needs to be proximally or distally attached to bone in the reconstruction of repaired ligaments to provide the appropriate stabilisation and enable the ligament to function as normally as possible.

5.8.6 Injury Prevention Methods

Ankle sprain prevention has been strongly recommended in sports with a high sprain incidence rate, such as basketball, volleyball, handball, soccer, rugby and running (Fong et al., 2007). Shoe type and the prevention of ankle sprain injuries should be investigated thoroughly as shoe type may play a role in preventing or causing ankle sprains. Robbins and Waked (1998) also suggest that footwear may help to correct foot position and thus reduce injury. The usefulness of rigid and semi-rigid supports in preventing ankle sprains is debatable and even may cause injury. As ankle sprains are a common injury future investigations exploring all possible devices that help in preventing the ankle sprain should be undertaken, with those increasing damage being avoided. The current study provided data on ligament behaviour in different joint positions which can be used in future investigations to produce appropriate ankle supports or devices that minimise or prevent ankle sprains.

This is not to say that the current study did not have its limitations. One of which was the age of the specimens examined (ranged 62 to 98 years). This may have resulted in degenerative changes in the ligaments resulting in a loss of fibrous mass affecting the ligament’s elongation or bony ossification and the extent of their attachment to bone. In addition, the range of motion (ROM) that was determined was not entirely realistic due to the necessity of the removal of muscles and other tissues around the ankle joint.

6 Conclusion

Previous studies have yielded either variable results or no information on the ankle collateral ligaments band number, exact bony attachments, dimensions, bony attachment lengths, ligaments behaviour or function. In addition, surgical reconstruction of these ligaments has been reported with a number of drawbacks, complications and movement limitations, which may be due to the lack of anatomical details. Therefore, the current study aimed to provide a comprehensive anatomical and functional knowledge of the ankle collateral ligaments. These aims included investigating anatomical variations, ligament dimensions, the exact bony attachment lengths and ligament behaviour in different joint positions.

6.1 Ankle Lateral Collateral Ligaments (LCL)

In the present study the ATFL had one, two or three bands, with the three band form being observed mainly in males, particularly in longer feet. The ATFL proximal attachment was to the anterior border of the lateral malleolus and the distal attachment to the body of the talus anteromedial to the anterolateral malleolar line (ALML). The anterolateral malleolar line (ALAML) was selected as a reference point due to its consistency and proximity to the ATFL distal attachment. The total proximal, middle and distal widths of the ATFL were significantly wider in the two and three band forms compared to the single band form. The calcaneofibular ligament (CFL) originated from the anterior border of the fibular lateral malleolus anterior to the lateral malleolar tip, sometimes extending to the tip. The site of the distal attachment was successfully defined in relation to the distance and angle to the fibular tubercle, with the majority of specimens attaching posterosuperior to the fibular tubercle, and the remainder posteroinferior.

More than half of the ATFL had no bony attachment. The ATFL was taut in plantarflexion and inversion and relaxed in dorsiflexion and eversion compared to neutral: no difference in the length of IATFL or MATFL was observed. The ATFL is considered a weak LCL ligament mainly restricting plantarflexion and inversion as well as the talar internal rotation and adduction that occurs in plantarflexion. The CFL responded variably in different joint positions, which could be due to the nature of its proximal attachment to the anterior border of the lateral malleolus as well as the shape and variable sites of its distal attachment. The CFL was considered to be stronger than the ATFL, due to its morphological features. It mainly restricted dorsiflexion, but also responded in neutral and eversion. Its proximal attachment to the anterior border of the lateral malleolus may aid in limiting fibular abduction and external rotation that can occur in dorsiflexion.

The PTFL was attached proximally to the malleolar fossa of the lateral malleolus, with its long distal attachment spreading on to the posterior part of the talar lateral surface and extending to the posterior surface of the talus with the majoity of specimens inserting lateral and superior to the talar posterolateral tubercle. The free length of the PTFL comprised approximately a quarter of its total length, while the distal bony attachment comprised more than half.

The PTFL is rarely injured due to its morphological qualities. It restricted dorsiflexion, while its proximal attachment to the malleolar fossa may limit the lateral malleolar abduction and external rotation that occurs in dorsiflexion. In addition, the long distal attachment to the posterior surface of the talus may prevent the talus from being posteriorly displaced or abducted, especially in dorsiflexion.

6.2 Ankle Medial Collateral Ligaments (Deltoid)

Injuries to the deltoid ligament have been reported in 72% of ankle instability cases; nevertheless it has been neglected by health professionals. In addition, variations and a lack of anatomical knowledge of the deltoid complex are reported in the literature: this may lead to underestimating or inappropriately managing injuries to the different parts of the ligament. The deltoid is composed of superficial and deep layers, with adipose tissue as well as small projecting fibres from both layers being observed. The superficial component of the deltoid consist of the tibionavicular (TNL), tibiospring (TSL), tibiocalcaneal (TCL) and superficial tibiotalar (STTL) ligaments, while the deep component comprised the posterior (PTTL) and anterior (ATTL) tibiotalar ligaments.

The proximal attachment of the TNL inserted mainly to the anterior border of the anterior colliculus of the medial malleolus. The distal attachment had a wide insertion to the dorsomedial surface of the navicular and the spring ligament. In the majority of specimens part of the deep part TNL component inserted to the talar medial surface as far as the neck. The TSL was a consistent band of the deltoid ligament, with four variable proximal sites of attachment, the most common being to the anterior border and medial surface of the anterior colliculus of the medial malleolus. The TSL distal attachment nearly always involved the spring ligament and the sustentaculum tali. Its free length comprised more than half of its total length.

The TCL was a consistent band observed in all specimens. The majority attached proximally to the medial surface of the anterior colliculus and medial surface of the medial malleolus superior to the edge of the intercollicular groove (MMSIG). The distal attachment was variable, with attachment sites including the medial surfaces of the talus and calcaneus, the sustentaculum tali, the talar posteromedial tubercle and spring ligament. The TCL had a free length of more than half the total length and was fully continuous with the STTL in more than half of the specimens, with the remainder having partial continuity. The superficial tibiotalar ligament (STTL) was observed in nearly all specimens. It originated from the medial malleolus but had variable sites of attachment, with the most common proximal attachment being superior to the edge of the intercollicular groove of the medial malleolus. Other sites of attachment were anterior to the posterior colliculus, the medial surface of the anterior colliculus and the anterior aspect of the posterior colliculus. The distal attachment of the STTL was to the medial surface of the talus, the posteromedial tubercle and sustentaculum tali. Two thirds of the ligament was free of any bony attachment.

The TNL was maximally stretched in plantarflexion and inversion and relaxed in dorsiflexion and eversion. It may restrict plantarflexion and inversion, limit talar adduction and internal rotation, while in plantarflexion the proximal attachment of a tensed TNL may restrict tibial external rotation. The TSL may provide supplementary support to the spring ligament in providing stability for the head of the talus. The complexity of TSL morphology, as well as its unusual shape and orientation, may be the reason why no change in length was observed suggesting an isometric function of the ligament.

The TCL was taut in neutral, dorsiflexion and eversion, and less so in plantarflexion and inversion. It limits dorsiflexion and eversion as it acts across both the ankle and subtalar joints. In dorsiflexion, the proximal attachment to the medial malleolus resists tibial internal rotation, while the distal attachment to the talus resists talar abduction and external rotation. The STTL was taut in neutral, dorsiflexion and eversion and less so in plantarflexion and inversion. It restricts dorsiflexion and eversion, as well as stabilising the ankle joint in neutral. In dorsiflexion the STTL proximal tibial attachment may limit tibial internal rotation, while the distal talar attachment may resist talar abduction and external rotation.

The posterior tibiotalar ligament (PTTL) was a consistent band of the deep layer, having one, two or three bands: one specimen had four bands. The three band form restricted inversion to a greater extent than the other forms. The TSL, TCL and STTL all cover or were superficial to the PTTL. The PTTL proximal attachment was between the posterior aspect of the anterior colliculus and the anterior aspect of the posterior colliculus filling the intercollicular groove

The PTTL inserted distally to the medial surface of the talus inferior to the medial malleolar articular surface, with the most common location of the APTTL insertion being anterosuperior to the posteromedial tubercle in the one, two and three band forms. In all PTTL bands the ligament had a free of more than half its total length. The PTTL may be considered as a strong ligament that restricts dorsiflexion and eversion, as well stabilising the ankle joint in neutral. In dorsiflexion its tibial proximal attachment may resist excessive tibial internal rotation, while the distal talar attachment may minimise talar external rotation.

The anterior tibiotalar ligament (ATTL) was almost always present, with the two band form seen in nearly 1/3rd of specimens, almost half of which were bilateral. Ligaments covering the ATTL were variable including the TNL, TSL and TCL and PATTL. Single ATTL mainly attached proximally to the medial surface of the anterior colliculus and its tip. In the two band form the AATTL attached proximally to the medial surface of the anterior colliculus and to its tip; while the PATTL was mainly attached to the medial surface of the anterior colliculus.

Irrespective of the form of the ATTL more than half of its total length had no bony attachment. The single ATTL limited plantarflexion and inversion, while in the two band form the AATTL limits inversion, plantarflexion and eversion, while the PATTL may guide the movement. In plantarflexion, the tibial proximal attachment may resist tibial external rotation, while the distal talar attachment may resist internal rotation of the talus.

6.3 Ankle Collateral Ligaments (Clinical Relevance)

Knowing the morphology of the lateral and medial collateral ligaments of the ankle, as well as their behaviour in the different joint positions, may help in evaluating and understanding the mechanisms of injury. The ATFL is the most commonly injured of all ankle ligaments: it can be injured in excessive plantarflexion or inversion, lateral malleolar avulsion fracture, fracture to the lateral talar process or when it is excised in surgical fixation of talar fractures. The CFL is the second most commonly injured ligament that may occur due to excessive movement: it is almost always combined with ATFL injury. The PTFL is rarely injured but when damaged it is usually combined with ATFL and/or CFL injuries. Deltoid ligament injury may result from excessive eversion, complex injury to the ankle, fracture of the lateral and medial malleoli, fracture of the talar neck, talar osteochondral lesion, overuse of the deltoid ligament due to insufficiency of tibialis posterior, or injury to the LCL: surgeons may also split the ligament during surgery to the sustentaculum tali.

Current approaches of surgical reconstruction or repair of injured ankle collateral ligaments have generally reported good results; however drawbacks include ankle and subtalar restrictions, the development of ankle instability later and scarifying the function muscles such as fibularis brevis. Additionally, many approaches with no long term outcomes have been published, with the drilling of bones and its effect on the vulnerability of fracture or injury has not been assessed. There is also a need for functional analysis in order to evaluate the role of the grafts used as well as the techniques of reconstruction in providing the required stability and preventing ankle instability.

The current study aimed to provide a strong anatomical and functional knowledge base of the ankle lateral and medial collateral ligaments, which could be interpreted with respect to the different repair or reconstruction techniques. Anatomical considerations in the surgical repair or reconstruction of the lateral and medial collateral ankle ligaments include the morphology and number of bands that will give surgeons a better visualisation of the composition of a specific ligament. The reported proximal and distal attachment sites of each ligament will provide surgeons with a standard method of identifying these sites to help with their proximal and distal repair. In addition, the current study has provided detailed dimensional information for each ligament that will be useful in the evaluation of the amount of fibrous loss during injury or the dimensions of ligament that need to be repaired.

Ligament behaviour (elongation or shortening) data observed in the present study will help surgeons understand how each ligament functions and behaves in different movements and how it should be orientated to retain ligament morphology with the appropriate behaviour to function normally. Moreover, the current study also provided the bony attachment lengths to enable the extent of a ligament that should be attached to bone proximally and/or distally in order to provide a repaired or reconstructed ligament with the same extent for stabilisation as before. These anatomical considerations will help develop better surgical approaches that involve repair or reconstruction of injured ligaments and retain the stability, restrictive and other characteristics that enable a ligament to function at its full potential.

Sports such as basketball, volleyball, handball, soccer, rugby and running have the highest incidence of ankle sprains; therefore preventing such injuries is important for these players and to anyone else at risk of an ankle sprain. However, the usefulness of the current preventive methods is debatable. The details of ligament behaviour presented in the current study will provide a good base of assessing and producing appropriate preventive methods or devices.

The current study provides a comprehensive understanding and knowledge base of the functional anatomy of the ankle collateral ligaments. This knowledge will aid understanding, diagnosis and surgical treatment of ankle collateral ligaments injuries. In addition, it supports an understanding of the mechanism of injury enabling the production of preventive or orthotics devices and appropriate shoes that can minimise damage or injury to these ligaments.

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8 Appendices

Appendices in this thesis include:

- **The anatomy of the superficial component of the deltoid ligament of the ankle: published abstract**
- **The deep posterior tibiotalar ligament (PTTL): published abstract**
- **Morphology of the calcaneofibular ligament: published abstract**
- **Anatomy of the anterior talofibular ligament (ATFL): published abstract**
- **The anterior talofibular ligament: a detailed morphological study: published article**

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Meeting Abstracts

Abstracts presented at the Winter Meeting of the British Association of Clinical Anatomists on 8th January 2015 at the Centre for Comparative and Clinical Anatomy, University of Bristol, Bristol, United Kingdom

ABU-OMAR, AHMAD, MICHAEL CRAWFORD, ASER FARGHAL, Department of Radiology, Norfolk and Norwich University Hospital, Norwich, United Kingdom. **A recurrent varicocele due to an anomalous left testicular vein: a case study**

Varicoceles occur commonly on the left side due to several anatomic factors, including the angle at which the left testicular vein enters the renal vein and the lack of effective antireflux valves at the junction of the testicular and renal veins. Anatomical knowledge of the different groups of pampiniform plexus (PP) and Bahren's classification of left testicular vein anomalies is of paramount importance in the management of varicoceles. Unfortunately, descriptions of the pampiniform plexus in the literature are confusing and controversial. We present the case of a 25-year-old man who underwent successful endovascular embolisation for a left-sided varicocele. He re-presented a year later with recurrence at the same side. The patient underwent angiography which revealed no reflux into the previously embolised gonadal vein. However, minor drainage was demonstrated via the posterior branches of the internal iliac veins but was not amenable for endovascular embolisation due to the absence of large incompetent veins. We present high resolution angiographic images of the rare anomalous PP. Clinicians should be aware of the various PP groups and left testicular vein anomalies for successful treatment of varicoceles.

ABU-OMAR, AHMAD, JOHN CURTIN, Department of Radiology, Norfolk and Norwich University Hospital, Norwich, United Kingdom. **Paratracheal air cysts: Anatomy, prevalence and clinical significance**

Paratracheal air cysts (PTACs) are benign tracheal diverticula characterized by single or multiple invaginations of the tracheal wall. We undertook a systematic literature review to ascertain the anatomical distribution, incidence, aetiology, and clinical relevance of PTACs. PTACs have a prevalence of around 2% and are either congenital or acquired. The may be produced by mucosal herniation due to increased intraluminal pressure. They occur at the thoracic inlet, almost exclusively on the right side. One large study reported that 98.5% of PTACs were located in the right posterolateral region and 1.5% in the left paratracheal region. The cysts were at the level of T1 vertebral body in 29% of patients, at T1-T2 in 17%, at T2 in 42% and at T2-T3 in 12%. PTACs can be mistaken for pneumomediastinum, apical lung herniation, laryngocoele, pharyngocoele and Zenker's diverticulum. They may cause chronic cough, recurrent pneumonia, stridor due to tracheal compression and recurrent laryngeal nerve palsy. We demonstrate PTACs on CT examinations of patients from our hospital. Clinicians should be acquainted with the appearance of PTACs to avoid misdiagnosis of other conditions.

ABU-OMAR, AHMAD, BALJEET DHILLON, DAVINA PAWAROO, Department of Radiology, Norfolk and Norwich University Hospital, Norwich, United Kingdom. **A rare case of a paediatric facial nerve schwannoma**

Facial nerve schwannomas are exceedingly rare. They can arise anywhere along the course of the nerve but have a predilection for the region of the geniculate ganglion. They usually cause lower motor neuron facial nerve palsy. Hearing loss and tinnitus are less common. We present a case of a left facial nerve schwannoma in a 15-year-old child with unexplained conductive hearing loss but surprisingly no facial weakness. An initial CT of the temporal bones demonstrated a soft tissue mass expanding the internal auditory meatus (IAM) and extending laterally to the cochlea and into the middle ear to displace the ossicles. The mass breached the roof of the internal auditory canal into the middle cranial fossa. Subsequent MRI of the IAM further characterized the mass, which had advanced from the cerebellopontine angle to the IAM, the geniculate ganglion and the horizontal portion of the facial nerve. We present high resolution imaging of this rare pathology and discuss the radiological anatomy of the facial nerve. Facial nerve schwannoma is uncommon. Clinicians should, however, consider this benign tumour in the context of unexplained hearing loss even in the absence of facial nerve palsy.

AHN KEUNHWI, WILLIAM PARTON, SAM HALL, JONNY STEPHENS, MATEUS GESTEIRA-ANDRADE, ELEANOR SEABY, ANDREW LOWRY, ALEXANDER DANDO, GEMMA SCRIMGEOUR, SCOTT BORDER, Faculty of Medicine, Centre for Learning Anatomical Sciences, Medical Education, Southampton General Hospital, University of Southampton, Southampton, United Kingdom. **Developing the National Undergraduate Neuroanatomy Competition: advancing careers in neurology and neurosurgery**

The National Undergraduate Neuroanatomy Competition (NUNC) is an exciting venture by a group of undergraduates and recent graduates in collaboration with the Centre for Learning Anatomical Sciences (CLAS). The NUNC encourages medical students to take responsibility for their own personal professional development and demonstrate their commitment to careers in neurology and neurosurgery through neuroanatomy. Currently no data exists regarding the variance in neuroanatomical knowledge of undergraduate medical students from across the UK. Research carried out by the group has shown that those studying at London medical schools performed better overall compared to those studying outside of the capital (55.8% vs 43.5%, $P < 0.01$). The mediating factors behind these findings are still unclear and remain a scholarly focus. As the competition develops academically, the NUNC has the potential to inform teaching practices in neuroanatomy education and provides a platform to influence future anatomy curricula. Furthermore it provides the opportunity to conduct nationally relevant educational research and is currently attracting partnering institutions for international collaboration. Alongside the CLAS near-peer teaching programme, the NUNC continues to reinforce the Faculty of Medicine's commitment to developing professionalism and becoming a centre of excellence for the undergraduate teaching of neuroanatomy.

ALATSATIANOS, ANTON, AMIR FARBOUD, SIMON BROWNING, ENT Department, Singleton Hospital, Sketty Lane, Swansea, Wales, United Kingdom. **Endoscopic middle ear surgery: Improved anatomical views**

The Conrad Lewin Prizes for the best presentations by young researchers were awarded to Abby Keable for the oral presentation entitled "Changes in ageing and in cerebral amyloid angiopathy of the perivascular clearance pathways for Aβ in the brain" and to Georgina Scarff for the poster presentation entitled "Blood supply to the splenic flexure and prevalence of collateral vessel Arc of Riolan in relation to ischaemic colitis".

turbinates. There appears to be a fixed ratio between the lengths and mucosal thicknesses of the inferior and middle turbinates. This ratio would undoubtedly be altered post-surgery and affect nasal airflow. An observational study to assess CT paranasal sinus scans pre- and post-septoplasty and trimming of inferior turbinates could be performed in future to further investigate the significance of this ratio.

KATTIMANI RAVI PRASAD, MORGAN BAYLEY, JAYNE SEBASTIAN, RAMESH BALASUNDARAM, Department of Orthopaedics, Glan Clwyd Hospital, Bodelwyddan Denbighshire, Wales, United Kingdom. **Is trochanteric bursitis influenced by pelvic anatomy? A retrospective radiological review of pelvic morphology in patients with trochanteric bursitis**

Trochanteric bursitis is a common cause of hip pain.We postulate that patients with wider pelvic morphology are more predisposed to develop trochanteric bursitis. Radiographs of the pelvis of 89 patients who had steroid injection for trochanteric bursitis between February 2010 and December 2012 were reviewed. Intertrochanteric distance and bispinal distance (between both ASIS), femoral neck angle and offset on AP pelvis radiographs were measured. A ratio of intertrochanteric to bispinal distance was calculated. We compared AP pelvic x-rays of an age and sex matched control group. Thirty-six patients were excluded from 89 because of inadequate pelvic x-rays. Of the patients, 81% were female and 19% were male. Mean age was 63 (range 30 – 90). Thirty-six percent had previous surgery to the affected hip. The average intertrochanteric distance and bispinal distance was 362 mm and 341 mm respectively. With an average ratio of 1.06 compared to 1.04 for the control group. We postulate that risk factors for trochanteric bursitis include female sex, increasing age, previous surgery, more varus femoral necks, larger femoral offset and wider pelvis. To allow for magnification of radiographs we would suggest the use of intertrochanteric to bispinal ratio in assessing patients with suspected trochanteric bursitis. We believe a figure of greater than 1.06 would be supportive of the condition.

KEABLE ABBY,[1] KATE FENNA,[1] ALI WADOOD,[1] HO MING YUEN,[1] DAVID JOHNSTON,[1] COLIN SMITH,[2] JAMES A.R. NICOLL,[1] JOHANNES ATTEMS,[3] RAJESH KALARIA,[3] ROXANA O. CARARE,[1] [1]Faculty of Medicine, University of Southampton, Southampton, [2]University of Edinburgh, [3]Centre for Brain Ageing and Vitality, Institute for Ageing and Health, Newcastle University, Newcastle upon Tyne, United Kingdom. **Changes in ageing and in cerebral amyloid angiopathy of the perivascular clearance pathways for Aβ in the brain**

The lymphatic drainage of Aβ from the brain occurs along the basement membranes of capillaries and arteries. We aimed to assess the pattern of deposition of Aβ in the basement membranes of leptomeningeal arteries in cerebral amyloid angiopathy (CAA) and to quantify the immunohistological profile of basement membrane markers in young, old and CAA brains. We tested the hypotheses that 1) Aβ is colocalised with basement membranes surrounding smooth muscle cells in CAA and 2) basement membranes change their composition with age. Brain sections (10μm thickness) from ten cases of severe CAA were stained by triple immunofluorescence for Aβ, smooth muscle actin and collagen IV and quantitative confocal microscopy was performed. Young ($n = 14$) and normal aged ($n = 20$) cases were immunostained for collagen IV, nidogen 2, fibronectin. Images were analysed using Image J, for percentage area stained. Statistical analysis was performed using one-way ANOVA. We found that there was a significant co-localisation between collagen IV and Aβ ($P < 0.01$) in tunica media. The percentage area stained with nidogen 2 was significantly higher in old compared to young brains. This study demonstrates that Aβ is deposited in the basement membranes surrounding smooth muscle cells, reflecting a possible failure of clearance along the lymphatic drainage pathways of the brain. We observed a significant increase in the amount of nidogen with normal ageing.

KELLY, CHRISTOPHER, PETER LOUGHENBURY, PAUL HARWOOD, SIMON BRITTEN, JENNIFER CLANCY, Division of Anatomy, School of Medicine, University of Leeds, United Kingdom. **Insertion of anteromedial wires in the application of a hind foot frame in distal tibial and calcaneal fractures**

External fixation using Ilizarov frames provides good outcomes for severe comminuted fractures, however, a safe angle of insertion has not yet been determined when applying hind foot frames for these fractures. This study investigated the risk to the posterior tibial neurovasculature (PTN) when anteromedial wires were inserted into the calcaneus. Twenty cadaveric limbs had 5 wires inserted into the calcaneus. In Group A, wires were inserted one third of the distance from the posterior tip of the heel to the tip of the lateral malleolus ($n = 50$). In Group B, wires were inserted halfway between these landmarks ($n = 50$). Angle of insertion was varied between $-10°$ and $50°$ in both groups. Vernier calipers were used to measure the distance between the wires and the PTN. There was a relationship between increasing angle of insertion and proximity to the posterior PTN in Groups A and B ($P < 0.05$ and $P < 0.01$ respectively). Based on these results, a maximum angle of 25° is recommended for insertion of calcaneal wires at one third of the distance from the heel. If greater bone purchase is required, a halfway insertion point may be used, with a maximum angle of insertion <10° decreasing risk to the PTN.

KHAWAJI, BADER,[1,2] ROGER SOAMES,[1] [1]Centre for Anatomy and Human Identification, University of Dundee, United Kingdom, [2]College of Medicine, King Saud bin Abdulaziz University for Health Sciences, Jeddah, Saudi Arabia. **The anatomy of the superficial component of the deltoid ligament of the ankle**

The superficial deltoid ligament, consisting of tibionavicular (TNL), tibiospring (TSL), tibiocalcaneal (TCL) and superficial tibiotalar (STTL) parts, was investigated in 54 formalin embalmed feet (27 right, 27 left; 19 male, 35 female). All parts were observed in all specimens, except STLL which was present in 92.4%. The TNL originates from the anterior border and/or medial surface of the anterior colliculus inserting into the dorsomedial surface of the navicular and talus: its length, width and thickness were 34.9 mm, 8.3 mm and 0.7 mm. The TSL extends from the anterior border and/or medial surface of the anterior colliculus to the spring ligament and/or sustenaculum tali: its length width and thickness were 30.9 mm, 6.1 mm and 0.8 mm. The TCL has various proximal attachments including medial surface of the anterior and posterior colliculi and superior to the intercollicular groove inserting into either the sustenaculum tali, spring ligament, talus or posteromedial talar tubercle: its length, width and thickness were 29.6 mm, 6.3 mm and 1.0 mm. The STTL attached superior to the intercollicular groove, anterior to the medial surfaces of the anterior and posterior colliculi inserting into the sustenaculum tali and/or talus and posteromedial talar tubercle: its length, width and thickness were 23.2 mm, 5.4 mm and 1.00 mm.

KHAWAJI, BADER,[1,2] ROGER SOAMES,[1] [1]Centre for Anatomy and Human Identification, University of Dundee, United Kingdom, [2]College of Medicine, King Saud bin Abdulaziz University for Health Sciences, Jeddah, Saudi Arabia. **The deep posterior tibiotalar ligament (PTTL): a morphological study**

Deltoid ligament injury may result from ankle fractures, sports injury and traffic accidents leading to medial ankle instability and chronic pain. The deep part of the deltoid complex, the posterior (PTTL) and anterior (ATTL) tibiotalar ligaments, is the main ankle joint stabiliser preventing external talar rotation and lateral talar shift. In an examination of 52 formalin embalmed feet (26 right, 26 left; 33 female, 19 male) the PTTL had one (5.8%), two (44.2%) or three (50%) bands. There were no significant relationships between the number of the bands and gender ($r = 0.11$) or side ($r = 0.16$). The PTTL extends between the anterior colliculus posterior part and the posterior colliculus anterior part filling the intercollicular groove of the medial malleolus. Its distal insertion is to the medial talar surface distal to the articular surface, varying from78.2% anterosuperior, 20.9% posterosuperior and 0.9% superior to the talar posteromedial tubercle (PMT). Distances and angles between the insertion points and PMT were 10.5 mm and 50.5° (anterosuperior), 7.5 mm and 101.5° (posterosuperior), 8.3 mm and 90° (superior). The mean length in neutral, midwidth and thickness were 15.3 mm, 9.4 mm and 1.4 mm. 54.9% of PTTL length had no bony attachment while 26% attached to the talus.

LAM, CHRISTINA, SAMANTHA LOW, DAVINA PAWAROO, Norwich Radiology Academy, Norwich, United Kingdom. **Branchial cyst: radiological anatomy of the neck and embryology**

Branchial fistulas, sinuses and cysts are types of branchial cleft abnormality which results from the persistence of branchial remnants that fail to obliterate *in utero*. They are the second most common congenital head and neck lesions in childhood, though most patients present during the second and third decades of life. We present a case of a 32 year old female with a longstanding discharging branchial fistula which spontaneously closed and later developed into a type II branchial cyst as per the Bailey classification (along the anterior surface of the sternocleidomastoid muscle, lateral to carotid space and posterior to the submandibular glands). Given this patient's classical presentation and radiographic location, a branchial cyst should be in the top differential as incision and drainage may hamper later attempts at definite surgical excision. It is important that clinicians make an accurate diagnosis as recurrence is rare after complete excision. Using magnetic resonance imaging (MRI), we review the anatomy of the neck and the embryological origins of neck structures. In particular, the focus will be on the possible anatomical locations for a branchial cyst as reported in the literature.

LEWIS THOMAS LORCHAN,[1] MATTHEW ALEXANDER BOISSAUD-COOKE,[2] TIMOTHY DY AUNGST,[3] CHARLES E. HUTCHINSON,[4] [1]Kingston Hospital NHS Trust, Kingston-upon-Thames, London, [2]North Bristol NHS Trust, Bristol, United Kingdom, [3]Department of Pharmacy, MCPHS University, MA, United States of America, [4]Warwick Medical School, University of Warwick, United Kingdom. **Radiological anatomy education, mobile technology and medical apps: Quo vadis?**

This review analyses the recent growths of mobile technology, medical applications in the context of radiological anatomy education. The growth in popularity in smartphones amongst clinicians since the introduction of the 'smartphone' and 'tablet' has been exponential given the visual nature of digital and the significant potential to use these devices to support day-to-day clinical radiology. However there is a significant and as yet underexplored area of literature related to the use of mobile devices, medical apps and their impact on radiological anatomy education. This review will highlight some of the novel tools and techniques, which are accessible to radiology trainees that may enhance their anatomy education. Further investigation of the quality of existing radiological anatomy apps alongside development of key criteria and guidance will enable users to assess and identify a useful radiology app. Recognition of the advantages and limitations of mobile devices and medical apps will enable trainees and educators to structure appropriately and complement their anatomy education by incorporation of mobile learning resources with traditional education programmes.

MACCHI, VERONICA, ANDREA PORZIONATO, GLORIA SARASIN, ANNA RAMBALDO, LUCIA PETRELLI, MARCO ROSSATO, RAFFAELE DE CARO, Institute of Human Anatomy, Department of Molecular Medicine, and Clinic of Internal Medicine, University of Padova, Italy. **Anatomical study of the infrapatellar adipose body**

Inflammation plays an important role in the pathogenesis of osteoarthritis. In the association between obesity and osteoarthritis a possible role of inflammatory properties of adipose tissue has been suggested. The infrapatellar adipose body, known as the body of Hoffa, can be regarded as a special form of adipose tissue due to its location, which is in close contact with synovial layers and articulating cartilage. The aim of the present study was to analyse the microscopic anatomy of the Hoffa's fat pad, using histological and ultrastructural methods. Twenty-five specimens of Hoffa's fat pad were sampled: 15 from subjects with osteoarthritis who underwent knee prosthesis, and 10 specimens from cadavers. Moreover, the volumetry of the Hoffa's fat pad was obtained from 20 cases of magnetic resonances exams. The Hoffa's fat pad consisted of white adipose tissue. In its substance vessels and nerves fibers were visible. The interlobular septa were thin, without elastic fibres. The surface of Hoffa's fat pad was covered by a thin synovial membrane with few vessels. In all the specimens with osteoarthritis hypertrophy of the synovial membrane with inflammatory cells infiltrations were found. A higher number of blood vessels was appreciable. Moreover, the fibrous interlobular septa were thicker. These data may support the hypothesis that the infrapatellar adipose body could contribute to the osteoarthritic disease process by producing and releasing inflammatory mediators, capable of modifying inflammatory and destructive responses in cartilage and synovial membrane.

MALLIA, ALVIN, NEIL ASHWOOD, Queens Hospital and Burton Hospital NHS Foundation Trust, Burton-on-Trent, United Kingdom. **A case of elbow synovial chondromatosis**

Synovial chondromatosis is a condition in which mesenchymal remnants of synovial tissue undergo metaplasia leading to the formation of cartilaginous nodules within the synovium. In advanced cases loose bodies form, occupying the synovial space resulting in patient discomfort and joint stiffness. Synovial chondromatosis typically presents as a monoarticular condition, with the knee being the most commonly affected joint. Other affected joints include the elbow, shoulder and ankle joints. The main symptoms are pain, swelling, and a limitation of movement in the affected joint. Changes in the joint can be see on radiographs, CT or MRI scans, with a definitive diagnosis being made histologically. Treatment consists of arthroscopic removal of loose bodies with or without a synovectomy. We report a case of a 49-year-old prison guard with synovial chondromatosis affecting the elbow joint. Clinical examination revealed a significant increase in the size of the elbow with a significant reduction in the range of movement between 40- 120 degrees. Simple radiographs demonstrated calcified bodies within the joint space. He underwent arthroscopic removal of the loose bodies. Postoperative evaluation at 6 months showed a marked improvement in the range of motion. He returned to playing golf without his previous discomfort.

MANSON, AMY,[1,2] MATTHIEU POYADE,[2] PAUL REA,[1] [1]Laboratory of Human Anatomy, School of Life Sciences, College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow, [2]Digital Design Studio, Glasgow School of Art, Glasgow, Scotland, United Kingdom. **Digital reconstruction of the ventricular system, and flow of cerebrospinal fluid around the brain and spinal cord**

The shape and size of the cerebral ventricles can be important in diagnosing and assessing medical conditions related to the flow of cerebrospinal fluid. However, with current medical imaging techniques, it can be difficult to visualise fully and understand this anatomy. Nowadays, the use of computer-aided learning can aid visualisation of complex 3D anatomy. The purpose of this study was to create an interactive educational and training package to aid the understanding of the cerebral ventricular system and the flow of cerebrospinal fluid.

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Abstracts

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ABOELMAGD TARIQ,[1] THOMAS JOVIC,[1] STEPHEN LARGE,[2] [1]University of Cambridge School of Clinical Medicine, Addenbrooke's Hospital, Cambridge, [2]Papworth Hospital NHS Foundation Trust, Papworth Everard, Cambridge, United Kingdom. **Adult case of anomalous origin of the left coronary artery from the pulmonary artery (ALCAPA).**

Anomalous origin of the left coronary artery from the pulmonary artery (ALCAPA) is a rare congenital anomaly. It is usually diagnosed in childhood due to its strong association with sudden cardiac death. We present the case of a 44-year-old woman diagnosed with ALCAPA following recurrent episodes of angina, dyspnoea and palpitations, who successfully underwent surgical management to create a two-coronary-artery perfusion system. We discuss this rare anatomical variant and the pathophysiological changes that occur with ALCAPA.

ABU-EL-HAWA NEFISSA, INGRID GOULDSBOROUGH, Faculty of Life Sciences, University of Manchester, Manchester, United Kingdom. **External indicators of the size of the vomer-ethmoidal junction (VEJ) angle**

The nasal septum is a midline structure in the nose which is composed of the perpendicular plate of the ethmoid, the vomer and the cartilaginous septum. The angle of the junction between the perpendicular plate of the ethmoid and the vomer (VEJ) has been shown to determine the level of deviation resulting from nasal trauma. Any external indicators of the VEJ angle would assist physicians in assessing the extent of any injury to the nasal septum. The length and width of the external nose was measured in 16 cadavers (12 male, 4 female). The heads were sectioned in the parasagittal plane to expose the nasal septum and the VEJ angle was determined. The mean length of the nose was 50.2 mm ± 1.4 mm, the mean width of the external nose was 26.1 mm ± 0.7 mm proximally and 37.6 mm ± 1.1 mm distally, and the mean VEJ angle was 75.1° ± 9.9°. The data collected demonstrated a high level of anatomical variation. It suggests that the external dimensions measured do not correlate with the VEJ angle. Other aspects of the external nose should be investigated.

AKITA KEIICHI, DAISUKE BAN, AKITOSHI NANKAKU, TAITO MIYOSHI, KUMIKO YAMAGUCHI, MINORU TANABE, Department of Clinical Anatomy, Tokyo Medical and Dental University, Tokyo, Japan. **Optimal cut line of the proximal jejunum on pancreatoduodenectomy according to findings of arterial distributions**

Pancreatoduodenectomy may be carried out to improve the prognosis of pancreatic cancer. The aim of this study is to examine the vessels distributing from duodenum to proximal jejunum in order to determine the optimal cut line of the proximal jejunum and mesentery. Eight adult Japanese cadavers were examined macroscopically for the distribution of arterial branches around the pancreas, the duodenum, and the proximal region of the jejunum. The inferior pancreatoduodenal artery (IPDA) and 1st jejunal artery formed a common trunk in seven cadavers. In all cases, branches of first jejunal artery were distributed principally to the duodenum and proximal jejunum, and there were many anastomoses between the first jejunal artery and IPDA. Thus, a dominant artery for lower head of the pancreas is not only the IPDA but also the first jejunal artery. Second jejunal artery independently supplied the proximal jejunum, and communications were rarely observed between the first and second jejunal artery without marginal arteries. The second jejunal artery ran on the left side of the superior mesenteric artery and the ventral side of the duodenum in the mesentery. In pancreatoduodenectomy, the optimal cut line of jejunum is the part between regions distributed by the first and second jejunal arteries.

ALASHKHAM ABDUELMENEM,[1] ABDULRAHMAN ALRADDADI,[1,2] ROGER SOAMES,[1] [1]Centre for Anatomy and Human Identification, University of Dundee, Dundee, United Kingdom, [2]College of Medicine, King Saud bin Abdulaziz University for Health Sciences, Saudi Arabia. **Morphological variations of coracoacromial ligament**

The coracoacromial ligament (CAL) morphology is variable and reported by many previous studies. There are 5 shapes of CAL: broad band (B), quadrangular (Q), Y-shaped (Y), V-shaped (V), and multiple-banded (M). Shoulders with rotator cuff disease showed changes in geometric and biomechanical properties of the CAL compared to normal shoulders. This study evaluates the distribution of CAL according to morphological shapes in relation to rotator cuff tear and acromial spurs. Two hundred and twenty embalmed shoulders were dissected and the CAL classified according to the 5 shapes morphology. The subacromial area was inspected for rotator cuff tear and acromial spur incidences. The 5 shapes of CAL were identified as follows: B = 16 (7%), Q = 20 (9%), Y = 49 (22%), V = 32 (15%), M = 100 (46%). A new crossing shape of CAL was identified in 3 (1%) shoulders. The multiple-banded shape was the most common ($P < 0.001$) and found more ($P < 0.022$) in sample of males than females (53%, 38% respectively). No relationship ($P > 0.05$) was detected between the CAL shapes and rotator cuff tear and acromial spurs, however more occurrences ($P < 0.030$) of acromial spurs were found in the sample of females (58%) than males (42%). Shoulders with cuff tears and spurs have longer and thicker acromial attachment ($P < 0.05$) than shoulders with none.

ALASHKHAM ABDUELMENEM, PAUL FELTS, ROGER SOAMES, Centre for Anatomy and Human Identification, College of Art, Science and Engineering, University of Dundee, Dundee, United Kingdom. **Histology and blood supply of the glenoid labrum**

The histology and the blood supply to the glenoid labrum were observed in 5 shoulders (2 males, 1 female). The glenoid labrum was divided into six regions: superior, anterosuperior, anteroinferior, inferior, posteroinferior and posterosuperior. Histologically, the glenoid labrum was found to be fibrocartilaginous, being more fibrous in the periphery. The posterosuperior, superior and anterosuperior regions of the glenoid labrum were triangular in shape and more vascular (mainly the superior and anterosuperior regions). The anteroinferior, inferior and posteroinferior regions were rounded in shape and less vascular. Circumferentially, the glenoid labrum is attached to both the hyaline cartilage of the glenoid fossa and to the bony part of the glenoid rim by penetrating fibres anchored deeply into the bone. It was observed that the glenoid labrum receives its blood supply from the

The Conrad Lewin Prizes for the best presentations by young researchers were awarded to Raj Subbu for the oral presentation entitled "Understanding proximal hamstring anatomy and successful clinical outcomes of proximal hamstring avulsion repair in athletes presenting within 6 weeks, 6 months and after 6 months of injury." and to Elham Shahbakhti for the poster presentation entitled "Osteoporosis and associated fractures in the post-medieval period, London (1547–1852)".

KASIRGA U. BARAN, Hacettepe University, Medical Faculty, Department of Anatomy, Ankara, Turkey. **Five hundred-year-old inspiration: Evaluation of ancient anatomical work of Leonardo Da Vinci to adapt them into the contemporary anatomical education and curricula**

It is a common practice in learning or teaching anatomy to use supplementary resources such as atlases. One of the best–known examples is the work of Da Vinci. In our study, we focused on approximately 250 drawings of Da Vinci which were released by the Royal Trust. We have surveyed the influence of those drawings on Anatomy. We have chosen several of them to adapt into our anatomical curricula. This study was carried out with 20 volunteer medical school students. Each of the study group members was asked to use a specifically designed notebook, and encouraged to make drawings and take side notes. Students are asked to draw at least one sketch similar to Leonardo's and one sketch completely of their choice. Examination results showed that the average grade of the Leonardo group was approximately 38% higher than the control group. Also in the Leonardo group, grades were not much further from the average and there were no extremely low or high points with a higher mode value. To increase the learner's compliance in anatomy, the learning experience has to be enriched. In conclusion, Leonardo's ancient anatomical work should be explored further to better utilize them.

KASKOVA-GHEORGHESCU ANNA, JENNIFER THOMPSON, School of Medicine and Medical Science, University College, Dublin, Ireland. **Vascular development in the chick extraembryonic membrane following cadmium exposure**

The vascular endothelium is a target of cadmium (Cd) toxicity. The effect of Cd on angiogenesis has been well documented, but not on vasculogenesis. This study investigates the effect of Cd on vasculogenesis in the chick model. Embryos incubated for 48 hours to Hamburger-Hamilton 13 were explanted according to Dugan's method and treated with 50 μl of 50 μmol CdAc vs Na Ac. After 8 hours, embryos were dissected, weighed, fixed, and processed for paraffin histology. After 24 hours, embryos were examined for branching morphometry using Fenton's method. Of control embryos ($n = 20$), 75% had formed omphalomesenteric vessels (OMV) vessels in line with developmental staging 8 hours post-treatment. In treated embryos ($n = 20$), 85% had delayed OMV formation ($P < 0.001$, Fisher's Exact Test). At 48+24 hours, OMV formation was evident in both groups, indicating that vasculogenesis was delayed but not prevented by Cd exposure. Embryo weights at 48+8 hours were significantly reduced in the Cd group (Cd: $n = 20$, 0.010 ± 0.003g vs. CTRL: $n = 20$, 0.021 ± 0.009g, $P < 0.001$, unpaired t-test). Histological examination revealed breakdown of continuity of the vascular endothelium in Cd group. Quantification of OMV vessels revealed that Cd inhibited vascular branching (Cd: 3. (Cd: 3.25 ± 1.21g vs. CTRL: 4.73 ± 1.33g generations of branching, $P < 0.001$, unpaired t-test).

KHAN NADER, SIMON GOODWIN, ANTHONY WILLIAMSON, KAREN ANKERS, ANAND PILLAI, NASSER KURDY, NAVEED YOUNIS, The Diabetes Centre and Department of Orthopaedics, University Hospital of South Manchester, Manchester, United Kingdom. **Charcot's neuroarthropathy: Functional outcomes**

The aims of the study were to ascertain the long-term functional outcome of patients with Charcot's neuroarthropathy. Data was obtained by the Short Form (36) Health Survey (SF-36) questionnaire to patients with diabetes who had been diagnosed with Charcot's neuroarthropathy and were attending routine clinic follow-up in a university teaching hospital. Fourteen patients out of 19 completed the SF-36, and their scores were compiled and analysed with other data. Of the 14 patients, 11 were male and 3 were female, with a total of 3 patients being diagnosed with Type 1 diabetes and 11 with Type 2. All 14 patients suffered from some degree of neuropathy. Patients that suffered with diabetes and Charcot's for a longer period of time had lower scores for physical functioning and experienced greater pain. The need for surgical treatment in this subgroup of diabetic patients is associated with reduced scores in physical as well as emotional health. Patients with higher body-mass index, produced evidence showing decreased scores for the majority of the SF-36 categories. Hypertension, amongst other co-morbidities, tended to greatly diminish the individual's physical functioning. This study provides significant qualitative data on the poor long-term quality of life and functional outcomes of patients with Charcot's neuroarthropathy and its impact on health.

KHAWAJI BADER, ROGER SOAMES, Centre for Anatomy and Human Identification, University of Dundee, Dundee, United Kingdom. **Morphology of the calcaneofibular ligament: The influence of joint position**

The calcaneofibular ligament (CFL) may be involved in lateral sprain injuries; however ankle instability and limitation of movement have been reported following surgical reconstruction protocols. The CFL was investigated in 45 feet from 23 formalin-embalmed cadavers (14 female, 9 male: 23 right, 22 left). It originated from the anterior border of the lateral malleolus, anterior to the tip in 88.6% and extended to the tip in 11.4%: the distance and angle between the tip and midpoint of the proximal attachment were 7.3 mm and 50°. The CFL inserted distally posterosuperior (81.1%) or posteroinferior (18.9%) to the fibular tubercle on the lateral surface of the calcaneus. The distance and angle between the fibular tubercle and the midpoint of the distal insertion were 16.4 mm and 15° (posterosuperior insertion) and 20.1mm and 12° (posteroinferior insertion). The mean lengths were 29.4, 30.6, 27.8, 28.9 and 30.2 mm in neutral and passive dorsiflexion, plantarflexion, inversion and eversion respectively. The width and thickness at the midpoint were 4.6 mm and 1.6 mm respectively. Of the CFL length, 28.7% was attached distally to the calcaneus; 62.5% had no bony attachment. A better understanding of CFL morphology will aid diagnosis, understanding of mechanisms of injury and treatment, especially surgical reconstruction.

KOLAR MALLAPPA K., GRAINNE BOURKE, Department of Plastic and Reconstructive Surgery, Leeds General Infirmary, Leeds, United Kingdom. **Congenital/infantile non-rhabdomyosarcoma soft tissue sarcomas of the upper limb: A case series**

Non-rhabdomyosarcoma soft tissue sarcomas (NRSTS) constitute 3% of all paediatric tumours. Of these, only one-third occur in those under the age of 6 years and only a few have been reported in the upper limb. The primary method of treatment is surgical resection. We describe 3 cases of congenital/infantile NRSTS presenting in the upper limb. Three children (1 male, 2 female) were referred with a mean age of 3.4 years (range: 2 months - 5 years old). Progressive increase in size of the tumour occurred over a mean period of 29.7 weeks (Range: 5 - 52 weeks). The NRSTS were found in the deltoid, upper arm and forearm and were resected with clear margins. As a result, microsurgical soft tissue reconstruction was performed (3 free groin flaps, 1 neurotised gracilis for reanimation of finger flexion, 1 nerve and tendon grafting). Follow-up at 3 years show all children free of disease. NRSTS are rare and early diagnosis, management in a multidisciplinary team setting and ensuring clear excision margins are critical for long-term successful outcome. Microsurgical reconstruction may be needed if presentation is delayed and can be complicated depending on the location and degree of infiltration of the lesion.

KOLAR MALLAPPA K., GRAINNE BOURKE, Department of Plastic and Reconstructive Surgery, Leeds General Infirmary, Leeds, United Kingdom. **The use of a pedicled sensate medial plantar flap not based on the posterior tibial artery: A case series demonstrating this as a reconstructive option**

The plantar skin is highly specialised in a number of regards including texture, vascularity and innervation, making it ideal to resist the demands placed. However due to this, reconstructive options are usually limited when plantar tissue is lost. One option is an advancement sensate medial plantar artery flap to use "like-for-like" tissue replacement and preserve sensation. The majority of blood flow to the medial plantar artery is derived from the posterior tibial artery but when compromised, the dorsal pedis is able to take over via

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ABOELMAGD SHARIEF,[1] JAMES MACKAY,[1] ASER FARGHAL,[1] SANDEEP KAPUR[2] [1]Department of Radiology, Norfolk and Norwich University Hospital, Norwich, United Kingdom, [2]Department of Surgery, Norfolk and Norwich University Hospital, Norwich, United Kingdom. **Sciatic hernia: A case 3Qstudy and review of anatomy of the sciatic region.**

Sciatic hernias are rare with no clear incidence in the literature, some studies stating less than 60 to be reported. They are defined as protrusion of the peritoneal sac and contents through the greater or lesser sciatic foramen. The anatomy of the region gives rise to a wide variety of possible clinical presentations from small bowel obstruction to sciatic nerve compression. Mr. E presented with constipation, gluteal mass, and altered position of the anal canal requiring the examining finger to be passed inferiorly toward the left thigh for rectal examination. CT imaging demonstrated a large left-sided sciatic hernia with protrusion of colon, rectum, bladder, and ureter through the defect. The defect was large such that there was no compromise to herniated structures. He was managed conservatively and is being followed up closely. We use this case to illustrate the anatomy of the region using CT imaging, outlining the herniated and surrounding structures.

ALASHKHAM ABDUELMENEM, ROGER SOAMES Centre for Anatomy and Human Identification, College of Life Sciences, University of Dundee, United Kingdom. **Origin of the long head of triceps**

The origin of the long head of triceps was observed in 10 shoulders (6 males, 4 females) and found to have an extended attachment of variable length. Besides its attachment to the infraglenoid tubercle, some fibers took origin from the posteroinferior aspect of the glenohumeral joint capsule as well as a fibrous slip from the upper aspect of the lateral (axillary) border of the scapula in all specimens. The mean width, and superior and inferior thickness of this extension on both sides in both sexes were 28.14 mm, 4.97 mm, 2.46 mm, respectively. The long head of triceps ran distally to unite with the medial and lateral heads before attaching to the olecranon process via a broad tendon. Anatomical variations with respect to both teres major and minor, the triangular and quadrangular spaces, the triangular interval and their neurovascular contents were not observed. An awareness of an attachment to the inferoposterior aspect of the fibrous joint capsule is important in arthroscopic or open shoulder surgery. A potential surgical complication is sectioning of these fibers leading to a change in shoulder movement and biomechanics.

ALOTAKI ERFAN, MOSTAFA NAGUIB, AMRO EL FEKY, RACHEL KOSHI Weill Cornell Medical College, Qatar. **Appraisal of the dissection experience by first-year medical students (Med1)**

First exposure to cadaver dissection has been shown to be stressful. This study reports how Med1 students of WCMC-Q appraise the dissection experience. Twenty-two of 41 Med1 students voluntarily participated in the study by anonymously completing the Appraisal of Life Events (ALE) Scale and Brief COPE questionnaires online. The ALE Scale was used to measure the impact of cadaver dissection. Three basic outcomes underlie such appraisals: challenge, threat and loss that relates to the potential for growth, potential for harm, negative effects on health or self-esteem respectively. Chi-square test was used to determine if the observed differences between percentages of responses to each of the outcomes was significant. The brief COPE scale was used to identify commonly used coping strategies. Significant differences were found in the students' appraisal of the dissection experience ($P < 0.001$), with subjects appraising the experience as challenging, with little threat or loss. Commonly used coping strategies were acceptance and positive reframing. We conclude that Med1 students in WCMC-Q find cadaver-dissection challenging, with little threat or loss. The coping strategies used are acceptance and positive reframing. These results are similar to those reported from other countries, but with some differences.

ALRADDADI ABDULRAHMAN, ROGER SOAMES Centre for Anatomy and Human Identification, College of Life Sciences, University of Dundee, United Kingdom. **The coracoacromial falx**

The coracoracromial ligament (CAL) extends between the anterior margin of the acromion and the posterior aspect of the coracoid process. Previous studies have noted that the lateral band is continuous with fibers of the joint tendon of coracobrachialis and short head of biceps; this is the coracoacromial falx. The purpose of this study was to determine whether a relationship exists between the falx and CAL morphology or impingement syndrome. Direct measurements were taken of the CAL in 147 shoulders from 81 formalin-embalmed cadavers: the rotator cuff muscles/tendons were also examined for the presence of tears. The falx was present in 65 shoulders (44.2%), with an average width of 4.68 mm, although the prevalence varied among CAL types: it was associated with a rotator cuff tear in 55% of shoulders. The anterior deviation angle of the coracoid process and the coracoid attachment width of the CAL were significantly increased in shoulders with a falx. When present the falx was continuous with the short head of biceps at the lateral aspect of the coracoid process. Although no significant relationship was found between the falx and CAL morphology or impingement syndrome, attention should be paid to the coracoacromial falx during surgery.

AL-TALALWAH WASEEM, ROGER SOAMES Centre for Anatomy and Human Identification, College of Life Sciences, University of Dundee, United Kingdom. **Arthralgia and gluteal claudication: Clinical features associated with the presence of a sciatic artery**

The superior gluteal artery (SGA) is a direct continuation of the posterior trunk of internal iliac artery (IIA) having a short course before it leaves the pelvis above the superior border of piriformis. It gives muscular and articular branches to the gluteal region and hip joint. In this study, the SGA was observed to have a variable origin and course in 68 specimens where it coexisted with a sciatic artery. The SGA arose directly and indirectly from the posterior trunk of the IIA in 80.3% and 16.7%, respectively. In 3% the SGA was considered to be congenitally absent. Aneurysm of the sciatic artery may present with gluteal claudication as well as arthralgia. Clinically, physicians and surgeons have to consider the patient history to achieve correct diagnosis. A delay in sciatic artery aneurysm diagnosis may have a poor outcome and prognosis. Radiologists also need to be aware of these anatomical variations to facilitate accurate reporting.

The Conrad Lewin Prize for the best presentation by a young researcher was awarded jointly to Miss Erica Tirr for the presentation entitled "Delineating the substructure of the thalamus using structural magnetic resonance imaging" and to Dr. Asif Naleem for the presentation entitled "Functional lengths of the lower limb arterial tree: Implications for interventional radiology".

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has increased. With this in mind a map of a "trigeminal nerve city" was constructed digitally. This was achieved using a programme called SketchUp, a three-dimensional modeling program intended for architectural, civil, mechanical and video game design currently utilized for building three-dimensional cities in Google Earth. The city comprises a fully signposted road which represents the trigeminal nerve, bridges represent foramina and famous buildings represent both cranial structures and the end points of each nerve branch. Students may either watch a pre-plotted pathway to guide them around the structure or alternatively they may explore it for themselves in the same way that they would tour a city via Google Earth. There is great potential to develop this resource into a vast network of cranial nerve cities. By adding other structures such as blood vessels, muscles and bones to the city a fully interactive learning guide can be achieved for relatively little cost.

KHALEGHI YASMIN, SHAMIMA NAHAR, HAROLD ELLIS St Thomas's Hospital, London, United Kingdom. **Negative rates of computed tomography kidney, ureter and bladder (CT KUB) in suspected acute renal colic**

Acute flank pain from suspected urolithiasis is a common hospital presentation, with radiological imaging playing an essential role in the diagnosis, management, and follow-up of patients. Traditionally, intravenous urography was considered the gold standard imaging modality for the investigation of renal colic, but this has largely been replaced by computed tomography kidneys, ureters, and bladder (CT-KUB). The objective of this study is to determine the positive rate for urolithiasis on CT KUB in male and female patients presenting to hospital with suspected acute renal colic. A retrospective review was carried out of 416 consecutive cases investigated with CT KUB over a two-month period between August and September 2012 at St Thomas's Hospital London. A total of 416 CT KUB scans were requested in patients with suspected acute renal colic, of which 219 (53%) were male and 197 (47%) female patients. The positive rate for urolithiasis was 44%. Female patients had a significantly lower positive rate for urolithiasis than male patients (31% vs. 56%; $P < 0.0001$). Ten percent of negative CT KUB scans revealed alternative pathology including gallstones, pyelonephritis, malignancy, appendicolith, renal cysts, phlebolith, and splenomegaly. 90% of negative CT KUB scans remained undiagnosed. We conclude that, although the presentation of renal colic is equal in the two sexes, the female patient presenting to hospital with suspected acute renal colic raises a particular diagnostic problem, as the occurrence of urolithiasis in female patients is significantly lower than in male patients. An improvement in current practice is necessary to lower female exposure to potentially harmful ionizing radiation.

KHAN MUHAMMAD A., SENTHOORAN RAJA, FARES S. HADDAD Department of Trauma and Orthopaedics, University College London Hospital NHS Trust, London, United Kingdom. **A review of the variable anatomy of the lateral cutaneous femoral nerve (LCFN) in relation to the anterior superior iliac spine (ASIS)—Implications in total hip arthroplasty (THA) performed using an anterior approach**

Lateral cutaneous femoral nerve (LCFN) injury during the anterior approach for THA has been reported in as high as 81% of cases. It frequently manifests as paraesthesia in the anterolateral thigh but may present as the debilitating syndrome meralgia paraesthetica. The variable anatomy of the LCFN places it at risk during surgery. Several studies have attempted to define these anatomical deviations. We reviewed twelve cadaveric studies examining 960 specimens in total. The LCFN typically exits the abdomen medial to the ASIS, however in a proportion of patients the nerve is either anterior or lateral to the ASIS where it is in danger of injury. We found that 19.3% (185/960) of the cadaveric specimens possessed a LCFN situated in an at-risk area in relation to the ASIS. The LCFN is usually found as a single trunk as it passes under the inguinal ligament (IL); however, it may divide either proximal or distal to the IL. Furthermore it may have a variable number of branches, up to five in some cases. A comprehensive understanding of the variability in the course and branching pattern of the LCFN is essential to successful anterior approach THA. We recommend that patients must be informed of this potential complication.

KHAWAJI BADER, ROGER SOAMES Centre for Anatomy and Human Identification, College of Life Sciences, University of Dundee, United Kingdom. **Anatomy of the anterior talofibular ligament (ATFL)**

The morphology and variations of the anterior talofibular ligament (ATFL) was investigated in 34 feet from 17 formalin-embalmed cadavers (11 females and 6 males). The ATFL originates from the anterior border of the lateral malleolus and runs anteromedially to the talus. One, two and three band forms of the ligament were observed in 25.8%, 61.3%, and 12.9% of the specimens respectively. The mean lengths of the various bands with the ankle joint in neutral, dorsiflexion and plantarflexion respectively were: superior band 21.27 mm, 20.24 mm, and 21.96 mm; middle band 15.97 mm, 16.96 mm, and 19.82 mm; and inferior band 17.75 mm, 17.83 mm, and 18.69 mm. The width of each band at the proximal attachment, at the midpoint and at the distal attachment respectively were: superior band 4.88 mm, 4.71 mm, and 3.98 mm; middle band 2.04 mm, 2.1 mm, and 1.99 mm; and inferior band 4.33 mm, 4.23 mm and 3.29 mm. The thickness of the superior band was 1.25 mm, of the middle 0.93 mm, and of the inferior 0.89 mm.

KHOYRATTY FADIL, THOMAS WILSON Department of Ear, Nose and Throat, Leeds General Infirmary, Leeds, United Kingdom. **The functional anatomical triangle of Guillain-Mollaret and its clinical implications**

Symptomatic palatal tremor is potentially the result of a lesion in the triangle of Guillain-Mollaret (1931) and associated with hypertrophic olivary degeneration [HOD] which has characteristic MR findings. The triangle is defined by dentate efferents ascending through the superior cerebellar peduncle and crossing in the decussation of the brachium conjunctivum inferior to the red nucleus, to finally reach the inferior olivary nucleus [ION] via the central tegmental tract. The triangle is completed by ION decussating efferents terminating on the original dentate nucleus via the inferior cerebellar peduncle. We can demonstrate the anatomy of this anatomical triangle using a clinical case of palatal tremor presenting with bilateral subjective pulsatile tinnitus along with the pathognomonic MR findings described previously. The hyperintense T2 signal in these patients may be permanent but the hypertrophied olives normally regress after 4 years. The temporal relationship between the evolution of the histopathology and the development of the palatal tremor remains unknown as does the natural history of the tremor. Botox injection at the level of tensor and levator veli palatini insertions has been used to treat patients with disabling tremor synchronous tinnitus.

LAYCOCK STEPHEN School of Computing Sciences, University of East Anglia, Norwich Research Park, Norwich, United Kingdom. **Creating 3D models from computerized tomographic (CT) data sets: can they aid in planning procedures?**

In recent years the process of creating three-dimensional models using three-dimensional printers or rapid prototyping machines has gained popularity. They have been used for a wide range of applications including art, design, medicine, and even for clothing. Computer procedures such as the Marching Cubes Algorithm can be used to construct geometric surfaces from a sequence of images such as the ones created in computed tomography and magnetic resonance imaging. By coupling these techniques with the advancements in three-dimensional printing it is now possible to produce relatively low cost and anatomically accurate patient-specific models to aid in the understanding of rare conditions and to assist in planning treatments. To investigate potential utility of three-dimensional printing, we investigate the processes involved when going from CT DICOM files to three-dimensional models. The test cases considered include the creation of a model of a tracheobronchial tree scanned from a patient with extensive tracheobronchial chondromalacia caused by advanced relapsing polychondritis and the construction of a model of a scapula with a very large lesion.

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The anterior talofibular ligament: A detailed morphological study

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HIGHLIGHTS

- Anterior talofibular ligament (ATFL): one (22.9%), two (56.3%) and three (20.8%) band forms.
- ATFL originates 10.37 mm anterosuperior to the fibular lateral malleolar tip.
- ATFL inserts to the talar body 3.92 mm anterior to the anterior lateral malleolar line (ALML).
- ATFL is most taut in plantarflexion (length: 21.06 mm) and inversion (length: 20.26 mm).

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ABSTRACT

The anterior talofibular ligament (ATFL) is commonly injured and may result in ankle instability. Good results from ATFL reconstruction have been reported; however complications and movement restrictions have also been observed. ATFL differences have been reported; however details of its precise bony attachment are lacking. This study provides a detailed morphology of the ATFL with respect to surgical and clinical applications. ATFL morphology, number of bands and the exact insertion points were studied in 50 formaldehyde embalmed feet. ATFL length was measured in different joint positions to assess its functional role: ATFL length varied from 18.81 mm in dorsiflexion to 21.06 mm in plantarflexion: mid-length width and thickness were 4.97 mm and 1.01 mm respectively. The bony attachment lengths were also measured: mean proximal and distal bony attachment lengths were 4.68 mm and 3.1 mm respectively, while 13.04 mm had no bony attachment. One (22.9%), two (56.3%) and three (20.8%) band morphologies were observed originating 10.37 mm anterosuperior to the lateral malleolar tip and inserting 3.92 mm anterior to the anterior lateral malleolar line (ALML). Detailed morphology of the ATFL may help in restoring injured ATFL function by appropriate ligament reconstruction, as well as aid the understanding of the mechanism of ligament injury.

1. Introduction

Ankle sprain is considered one of the more common injuries affecting ligaments of the ankle. In the UK approximately 5000 ankle sprains occur every day with some 27,000 occurring in the USA [1,2]. Injury to the lateral collateral ligament (LCL) due to ankle inversion comprises about 85% of ankle sprains [3–5]. Moreover, isolated anterior talofibular ligament (ATFL) injury and combined ATFL and calcaneofibular (CFL) injuries occur in 80% and 20% of cases respectively. It has been reported that an ankle sprain may involve avulsion fracture or soft tissue injury [2,6], in which two thirds of cases also have an isolated ATFL injury. It is estimated that 30–40% of untreated ankle sprains later result in chronic ankle instability [7], which is also pathologically common in individuals with serious ankle sprain or repetitive injury and may cause difficulty in some physical activities. Osteoarthritic changes in the ankle joint may also result from chronic ankle lateral instability [8].

Acute ankle injuries are usually diagnosed and their prognosis assessed on clinical examination, although magnetic resonance imaging (MRI) may help in assessing the healing process following ligament injury [9]. Accurate assessment of LCL injuries using MRI requires a good knowledge of the anatomy of the LCL and adjacent tissues [10]. Moreover, arthroscopy is used in visualising the ligament in reconstruction procedures [11]. A less invasive arthroscopic technique has been reported to have good results in treating chronic ankle instability with ATFL injury [12].

Different surgical techniques and approaches to reconstructing injured lateral ankle ligaments are available. Good results have

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been reported with some techniques: for example, a modified Brostrom approach produces good subtalar and ankle joint stability with a success rate of 85–95% [13,14]. Maffulli et al. [15] reported that the Brostrom technique is a safe procedure to restore sporting activity, although poor scores were reported in 21–24%, with recurrent instability in 16% of cases. Difficulties with some common surgical techniques have been reported [16–18], together with complications, including limitation of movement at the subtalar joint and ankle instability [4]. It is, therefore extremely important to have a good understanding of the relationship of the LCL complex, especially the ATFL, with respect to specific bony landmarks.

There is a lack of precision in the exact bony attachments of the ATFL as well as differences regarding its variations, including the number of bands present [19]. Prior studies reported variation in the existence of one, two and three band forms of the ATFL [18–24]. ATFL originates from the anterior border of the fibular lateral malleolus [25]. However, distal insertion of the ATFL was variable between the talar neck [25] and the junction between the body and neck of the talus [26]. The ATFL length was reported in previous literature is ranging between 13 mm and 40 mm [11,18,21,27–30]. The width was reported in a number of studies which was reported to be ranging between 4 mm and 12.98 mm [18,21,22,28,30]. Dimmick et al. [4] and Hua et al. [10] used MRI to measure ATFL thickness which was reported to be 2.19 mm and 1.46 mm respectively.

A more detailed understanding of the anatomy of the ankle ligaments should enable better diagnosis and treatment of ankle sprains. There will also be an improved understanding of the mechanism(s) of injury, especially of the ATFL, as well as establishing effective treatment protocols, including reconstruction techniques [31]. Although the most common factors that may put an individual at higher risk of injury are controversial [32], prevention and rehabilitation of ankle sprains concerns many medical professionals. Preventive methods such as taping and ankle braces [33] and balance training [34,35] help prevent future ankle sprains, especially in cases of previous injury. These can be improved and developed by studying ATFL variations and ligament behaviour, especially during movements that put different parts of the ligament at a higher risk of injury.

The aim of this study was to investigate, in detail, the morphology of the ATFL with respect to surgical reconstruction by determining its exact proximal and distal bony attachments, the length of these attachments and changes in ligament length with respect to joint position. The latter will provide an understanding of the role of the ligament in providing stability in different joint positions. This study will assist in providing: (i) an improved diagnosis and surgical treatment of ATFL injuries; (ii) a better understanding of the mechanism(s) of injury; and (iii) more effective injury preventive protocols.

2. Materials and methods

Fifty feet (25 right, 25 left) were dissected from 25 European Caucasian formaldehyde embalmed cadavers (10 male, 15 female), with an average age of 83 years (range: 62–97 years). There was no indication of injury or surgical repair to the lateral collateral ligament complex of the ankle at the time of death.

Skin, fascia, muscles and tendons on the anterior and lateral aspects of the ankle were carefully removed to expose the anterior talofibular ligament. The tendons of extensor hallucis longus, extensor digitorum longus, tibialis anterior and fibularis tertius were sectioned to expose the ATFL. Care was taken to preserve as much of the ligament as possible; fat and fascia between individual bands of the ATFL was carefully removed to avoid damaging the individual fibres. However, some measurements were not taken

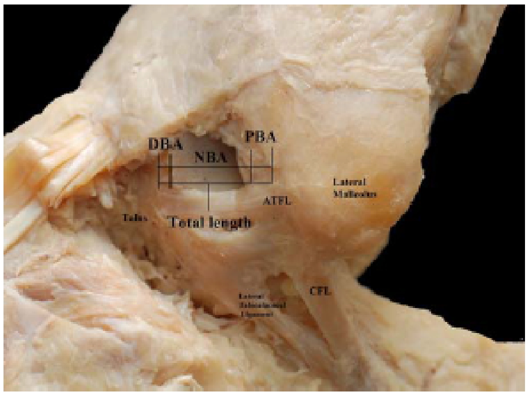

Fig. 1. ATFL length: no bony attachment (NBA), proximal bony attachment (PBA) and distal bony attachment (DBA).

in some specimens due to number of factors including ligament intactness and joint stiffness (movement limitation).

Variation in the number of bands and their orientation were recorded and photographs taken. Multiband ligaments were considered when separated sets of fibres had different distal insertions and/or directions, although some bands were not completely separate at the origin. When more than a single band was observed the superior band was taken as being the main component and referred to as the ATFL: additional bands were referred to as the inferior (IATFL) and middle (MATFL) bands when two and three bands were present.

Ligament length, width and thickness were measured using electronic digital Vernier callipers (Toolzone 150 mm; China), from the most proximal to the most distal attachment points with the ankle in neutral (foot at an angle of 90° to the leg): the ankle was secured in the neutral position passively while the length was measured; this was reliable as it was done by two other investigators with no significant difference. Ligament length was also measured with the ankle in maximum passive dorsiflexion, plantarflexion, inversion and eversion. It is acknowledged that the maximum range of each of these movement differed, consequently they were not standardised across specimens. All ligament length measurements were made to the ligament's longest fibres in each joint position. The free length, i.e. the non-bony attachment length (NBA) was also determined (Fig. 1) as the distance between the proximal and distal bony attachments. This reflects the length of the ligament that is subject to increasing tension during movement. The distal bony attachment (DBA) length was also determined, being taken as the distance between those fibres having a bony attachment distally and the last fibres at the distal point of insertion (Fig. 1). These measurements were only taken with the ankle in plantarflexion. The proximal bony attachment (PBA) was determined by subtracting the NBA and DBA from the total ligament length with the ankle plantarflexed (Fig. 1).

The width of each ATFL band was measured at three points: the mid-length of the ligament and at the proximal and distal attachments; the thickness of each band was measured at the mid-ligament length: the mid-ligament length was determined from the total length in plantarflexion.

The attachment of the ATFL to the lateral malleolus was determined, recorded and photographs taken. To enable a consistent description of the origin, a specific method was adopted in which the lateral malleolar tip was used as a bony reference point to identify the precise proximal insertion of the ATFL (Fig. 2). The distance and angle between the lateral malleolar tip and midpoint of the

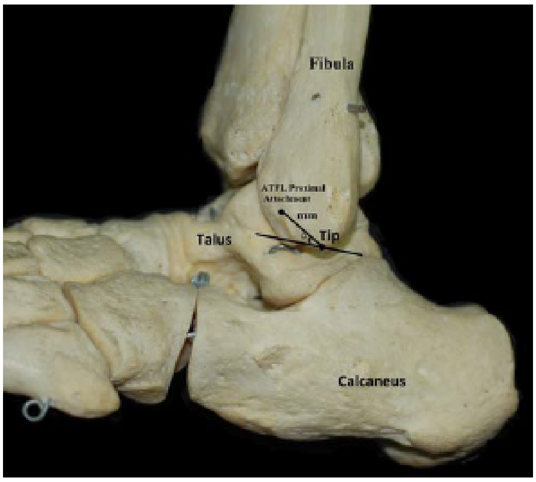

Fig. 2. The proximal attachment of the anterior talofibular ligament (ATFL).

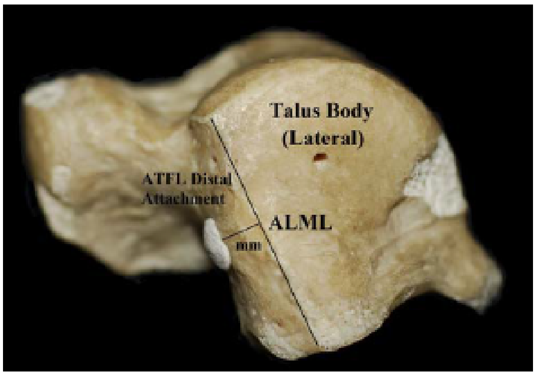

Fig. 3. Distal attachment of the anterior talofibular ligament (ATFL) in relation to the anterior lateral malleolar line of the talus (ALML).

proximal attachment of the ATFL were measured in the transverse plane; a parallel line to the transverse plane was drawn.

Similarly, the attachment of the ATFL to the talus was determined, and photographed, with respect to specific landmarks. The individual ATFL band attachments were identified in relation to the anterolateral malleolar line on the body of the talus (Fig. 3), with the distance between this line and the distal insertion point anteromedially measured.

The angle between the inferior border of the ATFL and the anterior border of the CFL was also measured (Fig. 4) to aid understanding of the relation between the ATFL and CFL and their interaction in producing an efficient and effective stabilising function.

To determine the relationship between various parameters foot length was measured as the distance from the midpoint between the medial and lateral calcaneal tubercles and the tip of the 2nd toe.

To assess the reliability of the measurements taken and repeatability of the methodology used five feet were selected at random and the lengths, widths and thicknesses of the various ATFL bands were repeated five times: on three separate occasions measurement were taken by the same individual and on two further

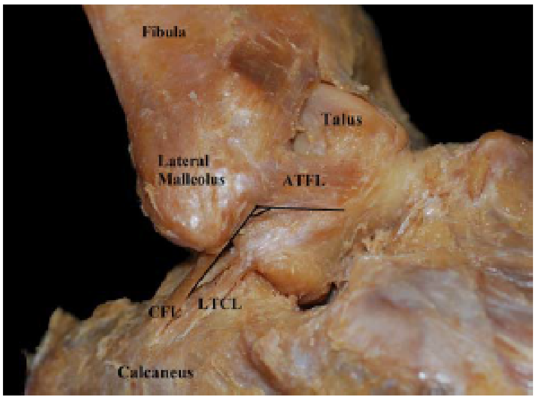

Fig. 4. Single band form of the anterior talofibular ligament (ATFL); LTCL (lateral talocalcaneal ligament).

Table 1
Number of anterior talofibular (ATFL) bands observed (n = 48).[a]

ATFL bands		1 Band	2 Bands	3 Bands
Bands form (n = 48)		11	27	10
Side (n = 48)	Right (n = 24)	4	14	6
	Left (n = 24)	7	13	4
SEX (n = 48)	Male (n = 19)	4	7	8
	Female (n = 29)	7	20	2
Morphology (n = 46)	Bilateral (n = 24)	6	16	2
	Unilateral (n = 22)	4	10	8

[a] Some measurements were not taken in some specimens due to number of factors including ligament intactness and joint stiffness (movement limitation).

occasions by different individuals. From these repeat measurements an interobserver and intraobserver analysis was undertaken using Kruskal–Wallis One Way Analysis of Variance on Ranks using SigmaPlot software for Windows Version 12.5 Build 12.5.0.38 Copyright© 2011 Systat Software, Inc.

Statistical difference of ATFL length in neutral position between male and female as well as between right and left sided feet was examined using t-test. Finally, the correlation between foot length and the number of the ATFL bands, length, width and thickness was analysed using Pearson Product Moment test using SigmaPlot software.

3. Results

Analysis showed that there was no significant difference, either within the same observer (P = 0.962) or between different observers (P = 0.974), in the repeated measurements taken. It can therefore be concluded that (i) the measurement protocol is reliable and (ii) the measurements taken are repeatable.

The ATFL was observed to have one (22.9%), two (56.3%) or three (20.8%) bands (Table 1): some multiple bands had connections to other bands but their distal insertions and fibre directions differed. A single band (Fig. 4) was observed in 11 feet (4 right, 7 left), 6 bilaterally and 4 unilaterally (one foot was not paired); two bands (Fig. 5) were observed in 27 feet (14 right, 13 left), 16 bilaterally and 10 unilaterally (one foot was not paired); and three bands (Fig. 6) were observed in 10 feet (6 right, 4 left), 2 bilaterally and 8 unilaterally. In males 8 specimens had three bands, with one and two bands being observed in 4 and 6 feet respectively. In contrast, in female specimens, the two band form was the most common (69%), with one and three bands being observed in 24.1% and 6.9% respectively.

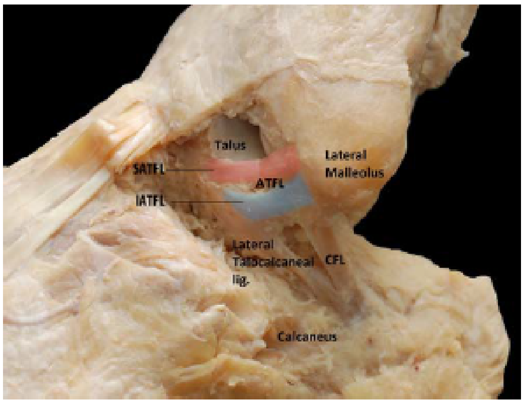

Fig. 5. Two band form of the anterior talofibular ligament (ATFL); LTCL (lateral talocalcaneal ligament).

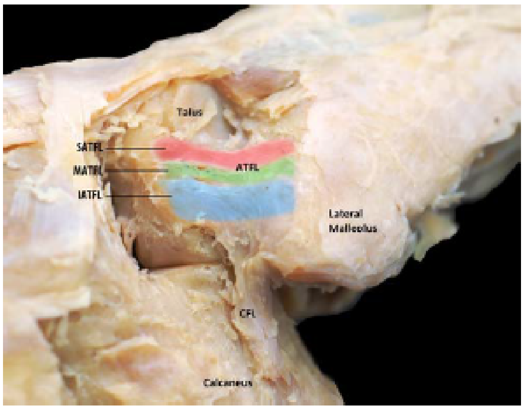

Fig. 6. Three band form of the anterior talofibular ligament (ATFL).

The ATFL originated from the anterior border of the lateral malleolus of the fibula (Fig. 2) 10.37 ± 3.44 mm anterosuperior to the tip of the lateral malleolus (LM) forming an angle of 62° with the malleolar tip and a line drawn parallel to the transverse plane. The fibres passed anteromedially to the distal attachment on the body of the talus 3.92 ± 1.33 mm anteromedial to the anterior lateral malleolar line (ALML) (Fig. 3); when present, the IATFL and MATFL attach 4.34 ± 2.36 mm and 3.63 ± 1.27 mm anteromedial to the ALML respectively. The mean angle between the ATFL and CFL was 121° (range: 78–155°) (Fig. 4).

The ATFL, IATFL and MATFL lengths in neutral (N), passive dorsiflexion (DF), passive plantarflexion (PF), passive inversion (IN) and passive eversion (EV) are shown in Table 2, together with the proximal, middle and distal widths and mid-length thickness. The length, width, and thickness of each ATFL band are given in Table 3. As can be seen the ATFL (superior band) was the longest, widest and thickest.

The length of the ATFL in neutral was significantly different between males and females ($P = 0.008$). On the other hand, there was no difference between the right and left sides in males ($P = 0.108$) or females ($P = 0.802$).

In the specimens studied foot length ranged between 17.5 cm and 25.3 cm. Relationships between foot length and the number of bands, ligament length, width and thickness were examined: there was a correlation between foot length and band number ($r = 0.357$), foot length and ATFL length ($r = 0.2430$, width ($r = 0.151$) and thickness ($r = -0.112$).

The proximal (PBA) and distal (DBA) bony attachment lengths, as well as the free (NBA) ligament length (Fig. 1) are shown in Table 4.

4. Discussion

There is an increasing interest in ankle and foot surgery, particularly in relation to diagnostic MRI of foot ligaments and foot rehabilitation: however a lack of detailed information on the ATFL may influence the effectiveness of ligament reconstruction, as well as the interpretation of MRI images. A detailed understanding of ATFL anatomy has become increasingly important for the accurate diagnosis of ankle sprains, interpreting the mechanism of injury, undertaking reconstructive procedures, supporting rehabilitation programmes and establishing efficient and effective prevention protocols. The majority of previous studies have not presented detailed information in relation to joint position or the precise attachment points: this study addresses these.

There is some dispute in the literature over the number of ATFL bands, with Golano et al. [19] highlighting these inconsistencies. In the current study 22.9% of specimens had a single band, with two and three bands being observed in 56.3% and 20.8% of specimens respectively: this supports Milner and Soames [20] and Ugurlu et al. [21], who both report the presence of one, two and three bands. Other authors [18,22,23] have reported one and two bands; however Sindel et al. [25] found only two bands. Sarrafian (1993) [24] is of the opinion that the ATFL mainly consists of two bands, but it may occasionally have three. Females most commonly had two bands, agreeing with Milner and Soames [25], while in males the three band form dominated. Such variations and observations may be related to different dissection approaches in which more or less associated soft tissue is removed or retained. In the current study, the ATFL was carefully dissected to expose and identify all

Table 2
Length (mm), width (mm) and thickness (mm) of the different bands of the anterior talofibular ligament (ATFL) in neutral, dorsiflexion, plantarflexion, inversion and eversion ($n = 47$).[a]

		n	ATFL	n	IATFL	n	MATFL
Length	Neutral	44	20.17 ± 3.4	32	16.54 ± 3.37	9	16.41 ± 4.84
	Dorsiflexion	44	18.81 ± 3.92	32	16.44 ± 3.88	9	17.04 ± 3.35
	Plantarflexion	46	21.06 ± 3.89	34	17.03 ± 3.67	9	18.99 ± 3.69
	Inversion	39	20.26 ± 3.25	27	16.27 ± 3.94	7	19.01 ± 4.04
	Eversion	37	18.25 ± 3.32	27	15.94 ± 4.21	7	18.19 ± 3.41
Width	Proximal	47	5.21 ± 1.52	34	4.2 ± 1.45	9	2.37 ± 0.91
	Middle	46	4.97 ± 1.46	33	3.86 ± 1.28	9	2.17 ± 0.78
	Distal	47	4.59 ± 1.41	34	2.98 ± 1.09	9	2.09 ± 0.71
Thickness	Middle	37	1.01 ± 0.35	26	0.65 ± 0.26	7	0.7 ± 0.31

[a] Some measurements were not taken in some specimens due to number of factors including ligament intactness and joint stiffness (movement limitation).

Table 3
Length (mm), width (mm) and thickness (mm) of each band of the anterior talofibular ligament (ATFL) in each of the configurations observed (n = 46).[a]

	Bands number	n	Length (PF)	n	Width (middle)	n	Thickness (middle)
ATFL	1 Band form	10	21.2 ± 5.67	10	6.02 ± 1.64	7	0.73 ± 0.34
	2 Bands form	26	20.92 ± 3.08	25	4.88 ± 1.16	21	1.13 ± 0.31
	3 Bands form	10	22 ± 4.34	9	4.03 ± 1.59	6	0.86 ± 0.34
IATFL	2 Bands form	26	16.57 ± 3.26	24	4.03 ± 1.19	20	0.62 ± 0.24
	3 Bands form	8	19.53 ± 3.32	8	3.54 ± 1.51	5	0.83 ± 0.32
MATFL	3 Bands form	9	18.99 ± 3.69	9	2.17 ± 0.78	7	0.7 ± 0.31

[a] Some measurements were not taken in some specimens due to number of factors including ligament intactness and joint stiffness (movement limitation).

Table 4
Lengths (mm) of the proximal (PBA) and distal (DBA) bony attachments, together with the free length (NBA), of the individual bands of anterior talofibular ligament (ATFL). Also shown are the percentage contribution of the PBA, DBA and NBA of total ligament length (n = 25).[a]

	NBA (mm)	% of total length (PF)	DBA (mm)	% of total length (PF)	PBA (mm)	% of total length (PF)
ATFL (n = 25)	13.04 ± 3.35	62.62	3.1 ± 2.11	14.90	4.68 ± 3.0	22.49
IATFL (n = 22)	9.92 ± 3.2	59.45	3.14 ± 2.4	18.80	3.63 ± 2.64	21.75
MATFL (n = 5)	13.42 ± 3.29	69.56	1.98 ± 1.3	10.28	3.89 ± 2.9	20.16

[a] Some measurements were not taken in some specimens due to number of factors including ligament intactness and joint stiffness (movement limitation).

ligamentous tissue present: the tissue was usually delicate and often adherent to the joint capsule and continuous with other ligaments, for example the lateral talocalcaneal ligament.

The ATFL attached proximally to the anterior border of the lateral malleolus (Fig. 2) 10.4 mm anterosuperior to the lateral malleolar tip, with which it formed an angle of 62°. Burks and Morgan [18], Sindel et al. [29] and Taser et al. [11] report the distance between the midfibular insertion and lateral malleolar tip as 10 mm, 10.0 mm and 13.3 mm respectively. Clanton et al. [36] reported that the distance between proximal insertion of single ATFL, superior band of ATFL and IATFL and the inferior tip of the lateral malleolus as 13.8 mm, 16.3 mm and 10.2 mm respectively.

Distally the ATFL attached to the most anterior part of the body of the talus (Fig. 3) 3.9 mm anteromedial to the ALML and not the talar neck as previously reported [10,20]; the IATFL and MATFL also attach to the talar body, being 4.3 mm and 3.6 mm anteromedial to the ALML respectively. Sindel et al. [25] reported the ATFL passing forwards to reach the lateral side of the talar neck, an observation not seen in the present study. Neuschwander et al. [26] observed the insertion to be at the junction between talar body and neck, which could be identified for placing surgical tunnels and interference screws. Previous studies give the distance between the ATFL mid-distal attachment and the subtalar joint as 18 mm [18] and 14.2 mm [25], while Taser et al. [11] reported the distance between the mid-distal attachment and superior and inferior surfaces of the talus as 14.77 mm and 17.03 mm respectively. Clanton et al. [36] identified the distal insertion of ATFL (single band) to be 11.3 mm to the anterolateral corner of trochlea of the talus and 17.8 mm to the apex of lateral talar process. Knowing the precise ATFL attachments to the talus should aid ligament reconstruction, as well as provide a better understanding of ATFL function in its role stabilising the ankle joint.

In the neutral joint position the ATFL (superior band) had a mean length of 20.2 mm, similar to previous observations of 24.8 mm [18], 17.81 mm [27] and 22.37 mm [11], but shorter than the 30–40 mm of Testut and Latarjet [28,29] and longer than the 13 mm of Milner and Soames [30] or the 14.38–20.84 mm of Ugurlu et al. [21]. One reason for these differences would be ligament length taken without consideration of ankle joint position: in the current study ligament length was measured with the ankle in neutral. Furthermore, the methodology employed in previous studies is not always clear: for example whether the reported length was for a specific band or the average of all bands. ATFL length variation can be important in understanding the mechanical behaviour and properties of the ligament; however, according to McDermott et al. [37] there is no correlation between ATFL length and the occurrence of ankle sprains.

In contrast to Taser et al. [11], who reported the mid-length width to be approximately 60% of that proximally and distally; the current study found only small differences in the proximal, middle and distal widths. Ligament width was not determined in different ankle joint positions, as Raheem and O'Brien [22] reported no change. Previous studies have reported ATFL width but did not specify where the measurement was taken. To enable comparisons to be made the average of the proximal, middle and distal widths in the current study was determined (4.9 mm) and was similar to that of Testut and Latarjet [28] (4–5 mm), but less than that of Burks and Morgan [18] (7.2 mm), Raheem and O'Brien [22] (10 mm), Milner and Soames [30] (11 mm) and Ugurlu et al. [21] (7.61–12.98 mm). These differences are probably due to differences in measuring techniques, especially as many studies did not state whether the width was of the main band only or of the whole ATFL. The middle width of the ATFL and IATFL tend to be wider in the two band form (4.88 mm and 4.03 mm) in contrast to the three band form of ATFL (4.03 mm and 3.54 mm) (Table 3). Moreover, when three bands existed, the IATFL was observed to be wider than the ATFL in half of the specimens.

ATFL thickness has not been reported in many previous dissection based studies, even though it is important in understanding the ligament's morphology and vulnerability to injury. An MRI based study by Dimmick et al. [4] reported ATFL thickness to be twice (2.19 mm) that of the current study (1.01 mm), with Hua et al. [10] reporting ATFL thickness in normal ankles (1.46 mm) being less than in injured ankles (2.71 mm). Determining ligament dimensions from MRI images will to some extent be influenced by image resolution and slice thickness, and as such are not directly comparable to direct measurement. In addition, differences may also be due to the MRI studies being undertaken on living subjects, while the present study was on cadaveric specimens in which changes to ligament morphology may have taken place. The ATFL and IATFL lengths reported by Neuschwander et al. [26] (19.7 mm and 16.7 mm) and Sindel et al. [25] (19.1 mm and 15.2 mm) are similar to those in the present study (20.17 mm and 16.54 mm). The mid-length width of these bands was 4.92 mm and 3.68 mm in the current study and 6.7 mm and 4.5 mm in Sindel et al. [25]. Burks and Morgan [18] had earlier reported the IATFL to be 20 mm long and 4.6 mm wide. All studies confirm that the ATFL (superior band) is longer and wider than the IATFL, suggesting that it plays a greater role in maintaining joint stability. The MATFL in contrast had a length of 16.41 mm, mid-length width and thickness of

2.17 mm and 0.7 mm in the neutral position: the length is greater (14.46 mm) but the width (4.44 mm) less than that of Ugurlu et al. [21].

In contrast to Ugurlu et al. [21] who reported the three band length was less (14.38 mm) than the two band (18.74 mm) which was less than the one band (20.84 mm): the three band length in the present study was the greatest. However, in agreement with Ugurlu et al. [21] ATFL width was greatest in single bands and least in three bands. The observation in the present study that IATFL length was shorter and width greater in two bands compared with three agrees with Ugurlu et al. [21]. In the present study IATFL thickness was less in two bands compared with three, being 0.62 mm and 0.84 mm respectively.

A weak correlation ($r = 0.357$) was observed between foot length and the number of the ATFL bands, suggesting that longer feet may be predisposed to having more ATFL bands. There was, however no correlation between the foot length and ATFL length, width or thickness.

Changes in ligament length were investigated to provide a better understanding of ATFL behaviour in different joint positions. Length decreased in dorsiflexion (18.81 mm) and eversion (18.25 mm) compared to neutral (20.17 mm) and increased in plantarflexion (21.06 mm) and inversion (20.26 mm). Raheem and O'Brien [22] reported similar changes in dorsiflexion (14.5 mm) and plantarflexion (18 mm) compared to neutral (15.5 mm). Nevertheless, both sets of results confirm that the ATFL is most taut in plantarflexion. An MRI study by De Asla et al. [38] measured ATFL length in different joint positions, being 16.3 mm in neutral, 13.9 mm in maximum dorsiflexion, 20.8 mm in maximum plantarflexion, 17.4 mm in maximum supination and 14.8 mm in maximum pronation. These length changes were much greater than observed by Ugurlu et al. [21] and the present study: this probably reflects (i) the influence of image resolution and slice thickness as referred to earlier and (ii) differences in the maximum ranges of movement possible.

That the ATFL is most taut in plantarflexion and inversion corresponds to the most common ankle position when it sustains a sprain: inversion has been reported to be restricted by the ATFL [39]. In addition, De Asla et al. [38] demonstrated that ATFL mostly stretched and vulnerable to injury in plantarflexion and supination. However, the IATFL was most taut in plantarflexion and neutral, while for the MATFL it was inversion and plantarflexion. There are few reports on the length of the proximal (PBA) and distal (DBA) bony attachments of the ATFL or its free length (NBA). NBA length was 62% of the total ligament length in plantarflexion, with DBA being 15% and PBA 23%. Both Burks and Morgan [18] and Sindel et al. [25] observed that the ATFL distal and proximal attachment lengths were similar. The NBA length is continuous with the lateral joint capsule and as such its role in providing stability during movement is reinforced by the capsule. It is unclear whether this part of the ligament, if free from the joint capsule, would show changes in length: this would presumably depend on the direction of capsular fibres associated with the NBA.

For the IATFL, NBA, DBA and PBA were 60%, 19% and 21% of total length, while for the MATFL they were 70%, 10% and 20% of total length. Clanton et al. [36] reported the proximal footprint of single ATFL, superior band of ATFL and IATFL to be 56.8 mm^2, 38.4 mm^2 and 29.4 mm^2 respectively; while the distal footprint was 60.7 mm^2, 47 mm^2 and 42 mm^2 respectively. Moreover, in a CT study of dissected feet Neuschwander et al. [26] reported that the ATFL and IATFL had surface areas of talar attachment of 1.5 mm^2 and 0.9 mm^2; while the ATFL and CFL together had a fibular attachment of 3.48 mm^2: however, the number of specimens was small. In the current study, footprints were carefully identified by (i) physical measurement of the DBA (talus) and PBA (fibula) lengths and the proximal and distal widths of the ATFL; and (ii) providing the exact proximal and distal attachments in relation to the lateral malleolar tip and the talar ALML. Such information will help in understanding ligament function in providing stabilisation for the anterolateral aspect of the ankle joint. Furthermore, it gives additional information as to how much of the ligament needs to be reconstructed and reattached in order to provide the same area of anatomical attachment to avoid movement restrictions.

It is accepted that there are a number of limitations which need to be borne in mind when considering the results present here. The cadavers were between 62 and 97 years old, a fact which may have an impact on ligament dimensions, their appearance and length changes in different joint positions. There was no access to the past medical history of the cadavers, although care was taken to ensure that there was no evidence of a resolved injury by checking for any obvious injury or residual scar. It is also acknowledged that the range of movement in cadaveric feet will be different than in the living, which may be a result of the absence of weight bearing and the dynamic impact on the different muscles acting across the joint [40]. Finally, there may be some limitation to the range of movement of the ankle joint and associated elongation of the ATFL as a result of the embalming process.

5. Conclusion

One (22.9%), two (56.3%) and three (20.8%) band forms of ATFL were observed in this investigation. ATFL originates from the anterior border of the lateral malleolus; 10.37 mm anterosuperior to the lateral malleolar tip. ATFL inserts to the body of the talus; 3.92 mm anterior to the talar anterior lateral malleolar line. The length of ATFL is most taught in plantarflexion and inversion with a length of 21.06 mm and 20.26 mm respectively; therefore ATFL has a functional role in restricting the plantarflexion and inversion movements.

There is a general lack of detail regarding the precise attachments of the ATFL, the length of its bony attachments and ligament length in different joint positions. The current study provides such detail and a sound basis for surgical reconstruction by ensuring its attachment with an appropriate length to the correct bony regions on the talus and/or fibula. Consequently the repaired and/or reconstructed ATFL ligaments will provide improved stability for the patient with fewer complications, movement restrictions and limitations.

The changes reported in ligament length with joint position are important in aiding the understanding of ATFL function. Mechanisms of injury can therefore be better understood, resulting in the development of efficient and effective injury preventive protocols.

An ankle sprain is one of the most common injuries affecting the lateral collateral ligament, especially the ATFL, and needs to be diagnosed early and treated effectively, including surgical reconstruction in some cases. Untreated ankle sprains may lead to a number of complications, including chronic ankle instability and pain. Some observations in the current study are at variance with previous reports: nevertheless they enhance the understanding of the variations and function of the ATFL.

In summary, a sound anatomical and functional knowledge of the ATFL will aid in injury diagnosis, including MRI interpretation, surgical reconstruction and understanding the mechanisms of injury. These features will also be important in the orthotics industry and for sports shoe manufacturers by helping to establish more efficient and effective injury preventive protocols.

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